9 ANATAHAN

9.1 Introduction

The island of Anatahan, located at ~ 16°21′ N and 145°40′ E, is the southernmost island of the Northern Islands Municipality of the Commonwealth of the Northern Mariana Islands (CNMI). This island is situated 120 km north of Saipan and 40 km south of Sarigan. Elongated east–west, Anatahan is ~ 3 km wide and 9 km long with a land area of 33.91 km^2 (Fig. 9.1a). A compound summit caldera, formed by at least 3 craters, dominates Anatahan. The highest point, at an elevation of 788 m, is on the western rim of the west caldera. The calderas of Anatahan are surrounded by steeply sloping flanks (Fig. 9.1b), which continue for some distance underwater. Northeast of this island, a submarine volcano known as NE Anatahan rises to a depth of 460 m below the sea surface. Although previously inhabited, Anatahan currently has no permanent residents. This island was declared off limits because of volcanic activity that has been ongoing since the first known eruption in May 2003.

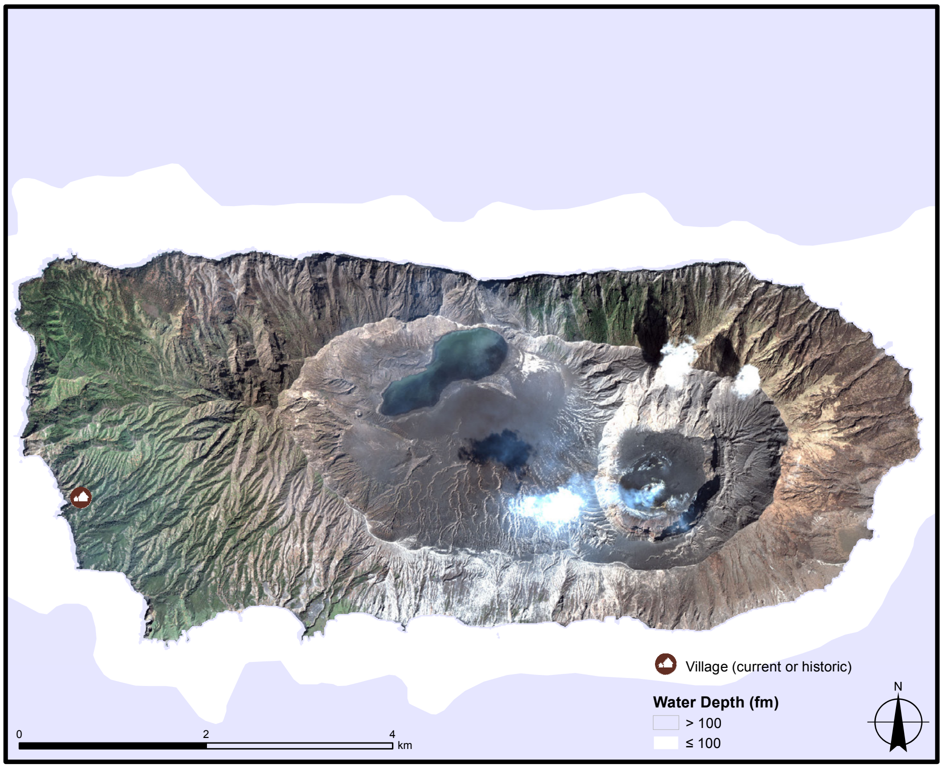


Figure 9.1a. Satellite image of Anatahan, labeled to show the historic village near the west coast (© 2005 DigitalGlobe Inc. All rights reserved).

Figure 9.1b. Anatahan, viewed from the southeast; the highest point of this island is on the western rim of the west caldera, and steeply sloping flanks surround most of this island. *NOAA photo*

9.1.1 History and Demographics

Anatahan has a general political history that follows the history of the CNMI as a whole, which is described in more detail in Chapter 1: "Introduction" and Chapter 8: "Saipan," Section 8.1.1: "History and Demographics."

Beginning in the early 1900s, small populations of < 50 persons have lived sporadically on this island, cultivating coconuts, corn, and sugarcane. When German administrator Georg Fritz visited Anatahan in 1901, he found no archaeological evidence of early Chamorro settlements (Spennemann 2006). A review of the population by German administrators in 1901 recorded 8 Chamorro and 3 Carolinian inhabitants on Anatahan; they probably were living there for copra production (Fitzner 1901; Cruz et al. 2000). During the period of rule by Japan, which began after World War I (WWI), limited copra production continued on Anatahan, supporting several Japanese and 45 Chamorro inhabitants. By the end of World War II (WWII), copra production had ceased, American authorities had moved Chamorro inhabitants to Saipan, and the only recorded residents on this island were a Japanese administrator and his wife. In 1945, this couple was joined by ~ 30 survivors of 3 Japanese ships that had been bombed and shipwrecked. In 1950, the administrator's wife left Anatahan after she was widowed, and, in 1951, following repeated efforts by the U.S. Navy to convince them that WWII was indeed over, the 19 remaining survivors surrendered and were picked up by an American detachment from Saipan (Trefalt 2003).

Anatahan has been mostly uninhabited in recent decades, because of the seismic and thermal activity of Anatahan Volcano. In 1993, following an earthquake swarm, the islands of Anatahan, Sarigan, and Farallon de Medinilla were declared off limits, and the island was subsequently evacuated again in 2003. Anatahan village, located in the southwestern section of this island, was covered with ash by the major eruption in 2003 (Siebert and Simkin 2002–).

9.1.2 Geography

Anatahan's compound caldera, as it appears in a digital elevation model (Fig. 9.1.2a), takes up nearly half of this island's surface and has a shape similar to the outline of this island. This caldera can be divided into east and west craters, each with different characteristics. The west caldera is ~ 2.3 × 5 km and has a floor of ponded lava with pyroclastic deposits (rock and dust ejected by volcanic activity). Before the 2003 eruption, the east caldera was 2 km wide and included 2 craters, an outer crater with a rim that joined the west caldera and a steep-sided, inner crater. The 2003 eruption formed a new, third crater within this east caldera; it is not yet known what other modifications may have occurred to this island's topography. The highest point on the rim of the east caldera is 540 m. Steep slopes surround this crater's rim and descend to the coast, cut with deep ravines (Siebert and Simkin 2002–).

The volcanic eruption that began on May 10, 2003, was the first eruptive activity recorded at Anatahan. Focused on the east caldera, this explosive vent eruption in 2003 was accompanied by pyroclastic flows (of volcanic ash, dust, and rocks down volcanic slopes), phreatic explosions (of steam, mud, rock, and other volcanic material caused by interactions of water and volcanic rock or lava), lava flows, and extrusion of lava domes. Ash plumes, continuing through the rest of May, were carried west by prevailing winds, and another explosion in June destroyed the lava domes in the east caldera's inner crater. From 2004 to 2006, volcanic activity continued with less intensity and various episodes of explosive eruptions, lava dome creation and destruction, and ash plumes. More recent recorded activity included a series of eruptions that began in December 2007 with ash and gas plumes continuing through August 2008 (Siebert and Simkin 2002–).

Anatahan was heavily forested historically but has been extensively damaged by feral animals, mainly pigs and goats; rats also have been observed on this island (Cruz et al. 2000; Atkinson and Atkinson 2000). The steep slopes around this island exacerbate effects of deforestation, and recruitment is prevented by feral ungulates feeding on seedlings. Even since 1994, when visiting scientists described a heavily forested island, significant habitat destruction has occurred (Cruz et al. 2000). Anatahan's vegetation, as surveyed in 2000, was primarily swordgrass with small pockets of trees and bare areas where disturbance had been greatest (Cruz et al. 2000). The May 2003 volcanic eruption destroyed much of the vegetation on Anatahan (Cruz et al. 2003).

9.1.3 Economy

Historically, the economy of Anatahan was centered on copra production, the level of which has varied over time. During the period of administration by Germany from 1899 through WWI, Anatahan was leased to the trading organization Pagan Gesellschaft for copra production (Spennemann 1999b). This product was the mainstay of the German economy in the

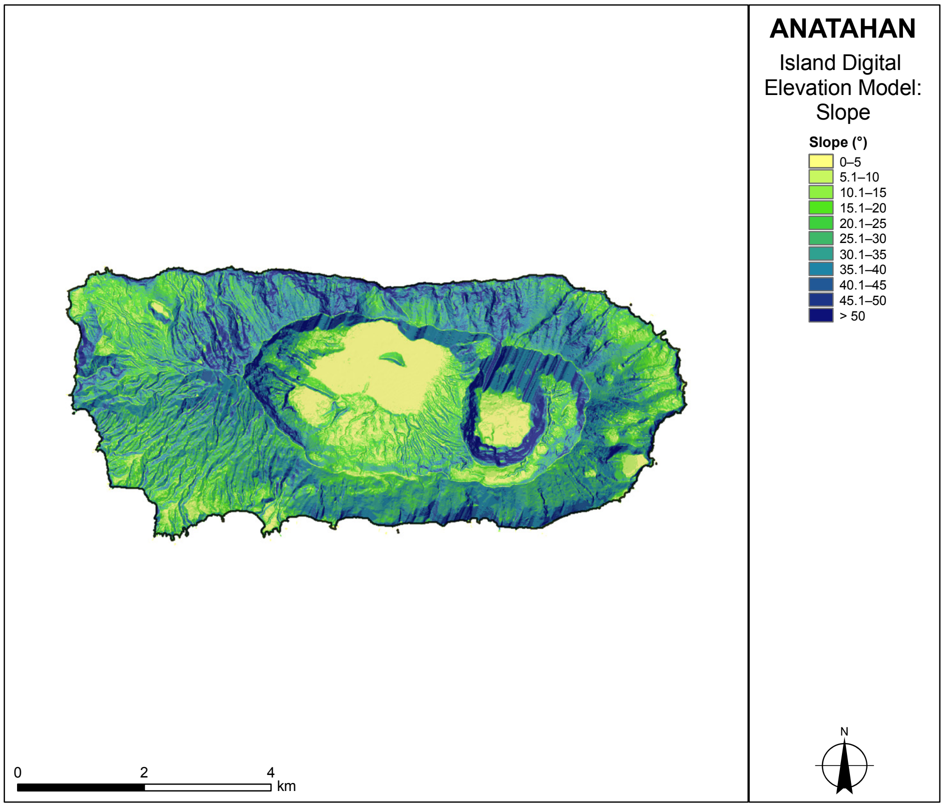


Figure 9.1.2a. Slope map using the digital elevation model (grid cell size: 10 m) for Anatahan. Values reflect the maximum rate of change in elevation between neighboring cells. This model was derived from data obtained prior to the 2003 volcanic eruption.

Marshalls Islands and in much of Micronesia; however, a series of typhoons between 1904 and 1907 resulted in a 50% reduction in production (Spennemann 1999b). More recent occupants of Anatahan, until their evacuation in 1993, probably relied on homesteading.

9.1.4 Environmental Issues on Anatahan

How badly marine habitats have been affected by volcanic activity is not yet fully clear. The only Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) surveys around Anatahan described in this report were conducted ~ 4 months after the beginning of the major eruption in 2003. Divers observed large volumes of ash covering coral reefs, mainly on the west side of this island. Ash plumes continued from 2003 to 2008 and, because of variable wind conditions, likely have affected other parts of Anatahan and the coral reef ecosystems around this island. Additional surveys are required to determine the extent to which reefs have been affected and whether signs of recovery on the worst affected areas are apparent. Low visibility in the waters around Anatahan in 2005 and 2007 prevented additional survey work; however, the Coral Reef Ecosystem Division (CRED) conducted limited surveys in 2009, the results and analysis of which will be presented in future reports.

The most significant land-based environmental issue on Anatahan is the high number of feral animals, such as goats and pigs (goats are thought to number ~ 6000; Cruz et al. 2000). These animals cause substantial damage to this island's native flora. The CNMI Division of Fish and Wildlife began a management program that focused on controlling this feral animal problem beginning in May 2002, but work subsequently ceased in 2003 because of volcanic activity (Cruz et al. 2003).

Anatahan supports only 4 species of forest birds: Micronesian honeyeater (*Myzomela rubrata*), Micronesian starling (*Aplonis opaca*), Micronesian megapode (*Megapodius laperouse*), which is listed federally as endangered (U.S. Fish and Wildlife Service) and locally as threatened or endangered (Berger et al. 2005), and very low numbers of the near-threatened (BirdLife International 2008) white-throated ground-dove (*Gallicolumba xanthonura*). This small number of species found on Anatahan is a consequence of this island's lack of suitable habitat, which results from destruction by feral animals (Cruz et al. 2003). A population of ~ 1000 Mariana fruit bats (*Pteropus mariannus mariannus*), an endemic subspecies listed federally as threatened (U.S. Fish and Wildlife Service) and locally as threatened or endangered (Berger et al. 2005), also has been observed on this island (Cruz et al. 2000; Cruz et al. 2003).

9.2 Survey Effort

Biological, physical, and chemical observations collected under MARAMP documented the conditions and processes influencing the coral reef ecosystems around the island of Anatahan since 2003. Because of poor conditions and safety concerns caused by volcanic activity, biological surveys around this island were limited in 2003 and not attempted in 2005 or 2007. More details about the extent and time frame of the survey effort around Anatahan are discussed in this section. The disparate areas around this island are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 4 geographic regions around Anatahan are delineated in Figure 9.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Anatahan. Potential reef habitat is represented by a 100-fm contour shown in white on this map.

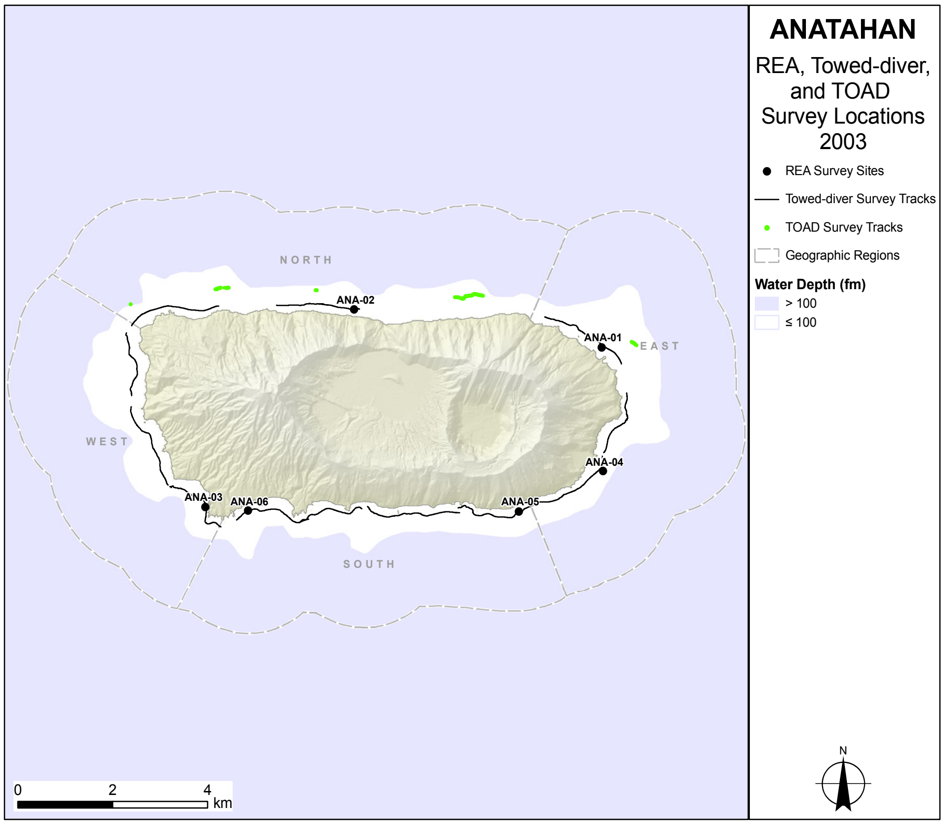


Figure 9.2a. Locations of the REA, towed-diver, and TOAD benthic surveys conducted around Anatahan during MARAMP 2003. To aid discussion of spatial patterns, this map delineates 4 geographic regions: north, east, south, and west.

Benthic habitat mapping data were collected around Anatahan using a combination of acoustic and optical-survey methods. MARAMP benthic habitat mapping surveys conducted around this island with multibeam sonar covered a total area of 2228 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 9.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Anatahan was collected using REA, towed-diver, and TOAD surveys during MARAMP 2003. The results of these surveys are reported in Sections 9.5–9.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003 are presented in Table 9.2a, along with their mean depths and total area and length.

Table 9.2a. Numbers, mean depths (m), total area (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Anatahan during MARAMP 2003. REA survey information is provided for both fish and benthic surveys, the latter of which includes assessments of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year
REA		**2003**
Fish	Number of Surveys	3
	Mean Depth (m)	11.7 (SD 3.2)
Benthic	Number of Surveys	6
	Mean Depth (m)	11.7 (SD 3.2)
Towed Diver		**2003**
	Number of Surveys	12
	Total Survey Area (ha)	21.2
	Mean Depth (m)	12.9 (SD 1.4)
TOAD		**2003**
	Number of Surveys	5
	Total Length (km)	1.07

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Anatahan were collected using (1) subsurface temperature recorders (STRs) designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005 and 2007, and water sampling was performed during MARAMP 2005 and 2007 (see Chapter 2: "Methods and Operational Background," Section 9.4: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 9.2b. Results are discussed in Section: 9.4: "Oceanography and Water Quality."

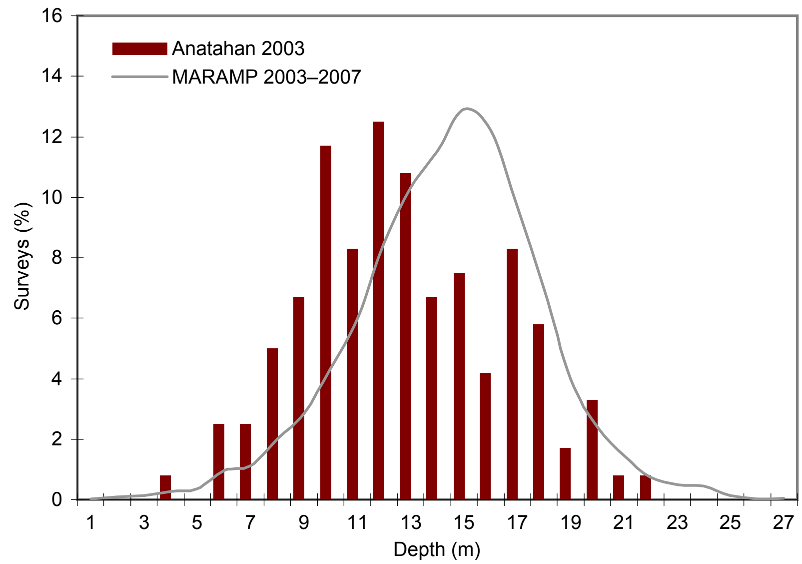
Table 9.2b. Numbers of STRs deployed, shallow-water and deepwater CTD casts performed, and water samples collected at Anatahan during MARAMP 2003. Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	**2003**	**2005**		**2007**		**2009**	**Lost**
	Deployed	**Retrieved**	**Deployed**	**Retrieved**	**Deployed**	**Retrieved**	
STR	2	1	1	1	1	1	1
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	25	3		3			31
Deepwater Casts	–	2		–			2
Water Samples		**2005**		**2007**			**Total**
		3		2			5

Towed-diver Surveys: Depths

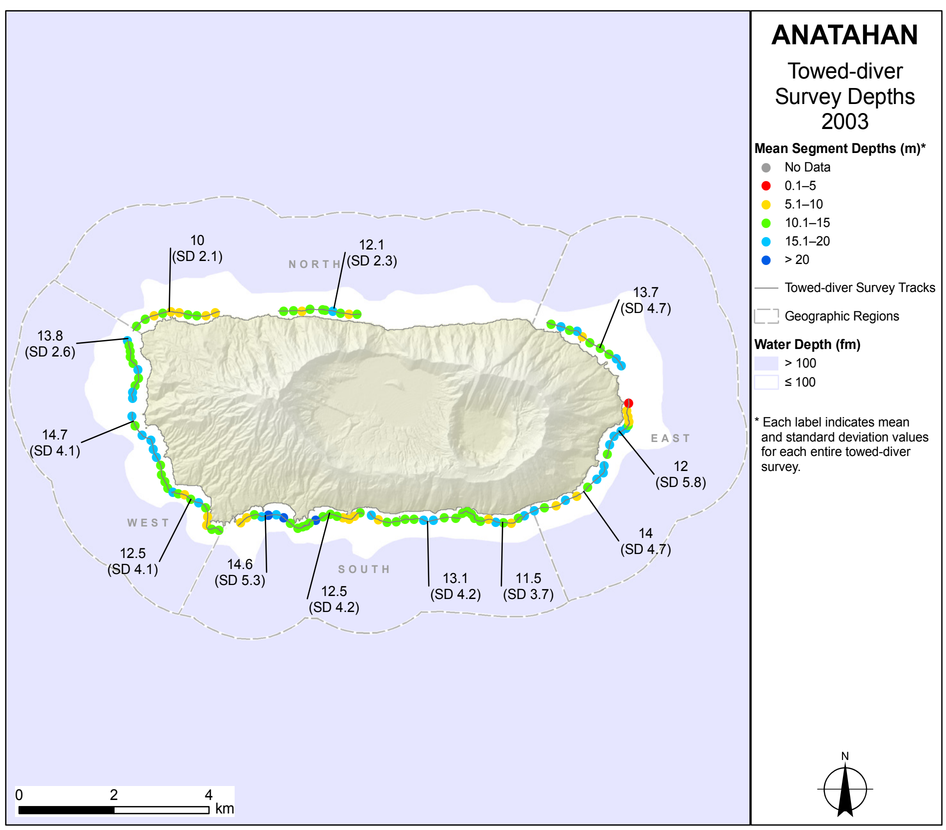
Figures 9.2b and c illustrate the locations and depths of towed-diver-survey tracks around Anatahan and should be referenced when further examining results of towed-diver surveys from MARAMP 2003.

Figure 9.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Anatahan during MARAMP 2003. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during 2003, 2005, and 2007.



During MARAMP 2003, 12 towed-diver surveys were conducted along the forereef slopes around most of Anatahan (Figs. 9.2b and c). The mean depth of all benthic survey segments was 12.9 m (SD 1.4), and the mean depths of individual surveys ranged from 10 m (SD 2.1) to 14.7 m (SD 4.1). Because of suspended ash particulates in the water column, visibility during most of these towed-diver surveys was highly restricted.

Figure 9.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Anatahan during MARAMP 2003. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.



9.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the island of Anatahan were conducted during MARAMP 2003 and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 400–1800 m. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of < 207 m.

9.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 9.3.1a) collected by CRED around the islands of Anatahan, Alamagan, Sarigan, and Guguan and Zealandia Bank during MARAMP 2007 encompassed an area of 2228 km^2. No specific acoustic survey was undertaken at Anatahan, but low-resolution multibeam data were obtained in 2007, using the NOAA Ship *Hi`ialakai* during recovery of a moored oceanographic instrument. Limited coverage was achieved north and south of Anatahan, and additional data were obtained along 2 transit lines north and northeast of this island. No shallow-water multibeam data were acquired using the R/V *Acoustic Habitat Investigator*.

No multibeam data were collected in nearshore waters; therefore, no high-resolution bathymetry data were available for analysis of slope, rugosity, or bathymetric position index zones. Because the area of interest for coral reef monitoring is limited to shallow waters, conducting these analyses using deepwater bathymetry data was not merited. Thus, in this section, deepwater multibeam bathymetry and backscatter data are presented, but no further derivatives, from either multibeam bathymetry or backscatter, are shown.

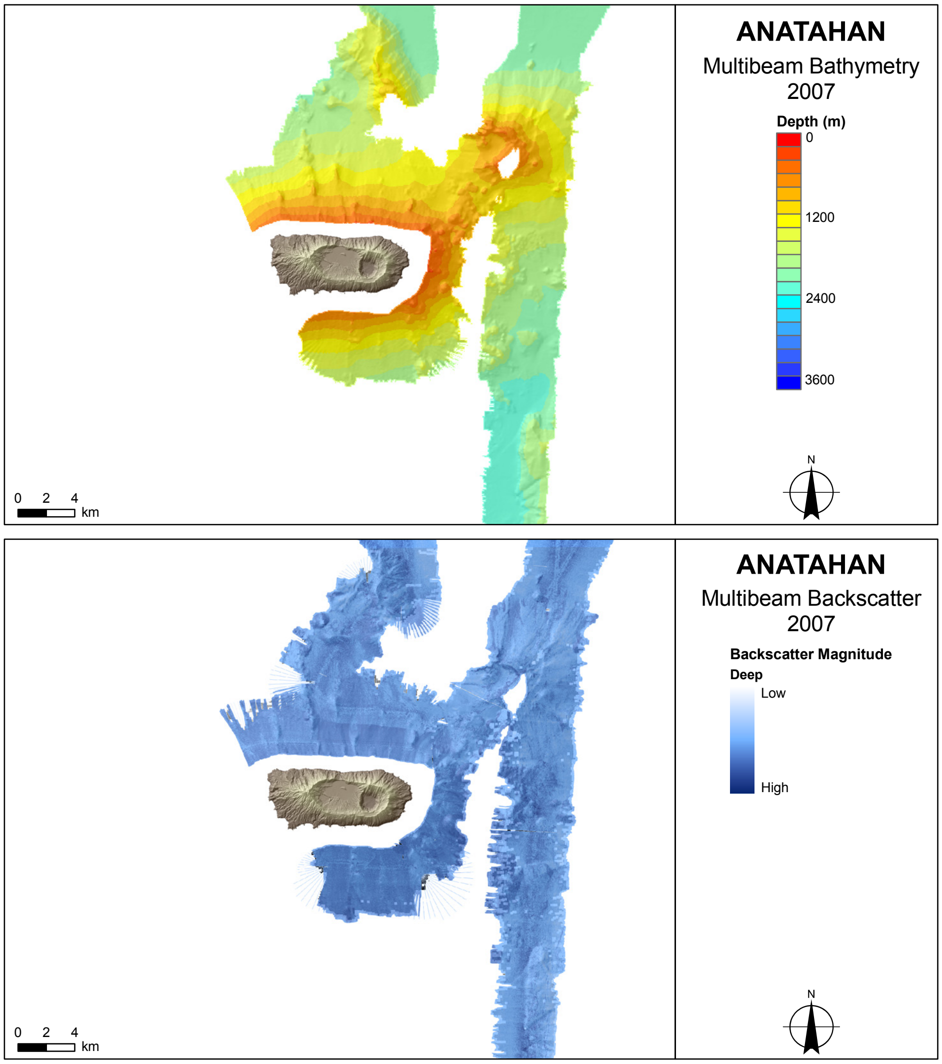
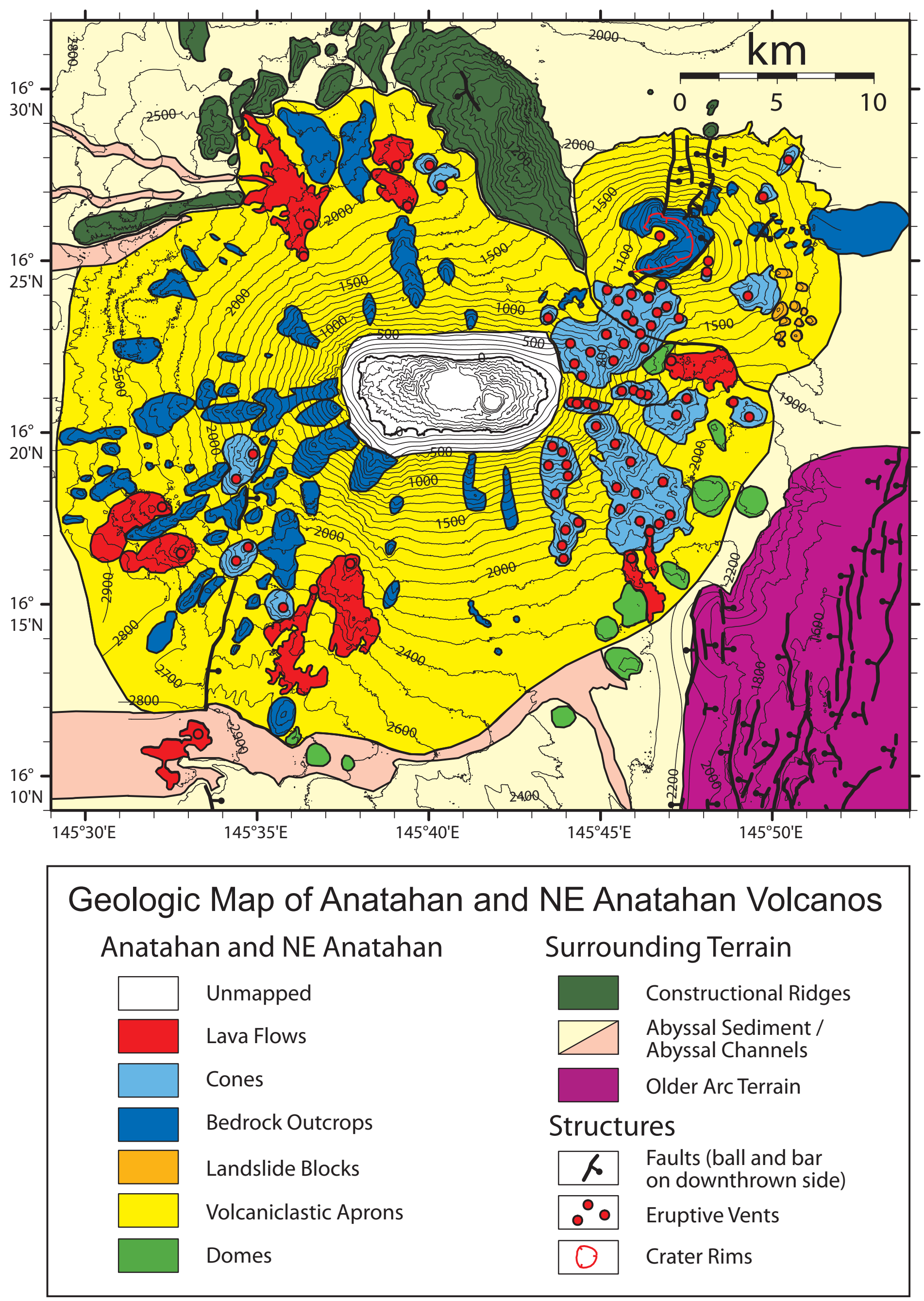


Figure 9.3.1a. Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Anatahan during MARAMP 2007 at depths of 400–1800 m. Deep-backscatter data (blue) were collected using a 30-kHz Kongsberg EM 300 sonar. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

The submarine flanks of Anatahan were also surveyed in 2003 and 2004 as part of the "Submarine Ring of Fire" project, which was funded by the NOAA Office of Ocean Exploration and the NOAA VENTS Program. As part of this project, volcanoes of the Mariana Arc were surveyed and multibeam bathymetry and sidescan data were acquired. Data from these surveys were collated and interpreted by Chadwick et al. (2005) and used to produce a geologic map for the submarine flanks of Anatahan Volcano. This geologic map is presented here (Fig. 9.3.1b) to provide context for the more limited data obtained by CRED.

A major volcanic eruption was recorded in May 2003 at Anatahan and volcanic activity continued through August 2008, as described in more detail in Section 9.1.2: "Geography." Because of this ongoing activity, keep in mind that data presented here only provide a snapshot of the nature of the seabed around Anatahan, which has been altered as a result of volcanic activity, such as lava flows and deposits of ash and coarser volcanic material.

Figure 9.3.1b. Geologic units and structures of the submarine flanks of Anatahan Volcano, including NE Anatahan, the satellite submarine volcano northeast of the island of Anatahan, from Chadwick et al. (2005).



The extremely limited coverage of the low-resolution multibeam data for Anatahan makes it difficult to draw many conclusions about the nature of the seabed around this island. North and south of this island, the limited CRED multibeam bathymetry data show flanks descending to a depth of ~ 1800 m at the limit of the data. Data presented by Chadwick et al. (2005; Fig. 9.3.1b) and the additional bathymetry obtained by CRED with the 2 transit swaths north of Anatahan suggest that these flanks continue to depths > 2000 m.

These same data also reveal 2 topographic highs north of Anatahan. The first, located directly north of Anatahan, rises to a depth < 1050 m from the ~ 2000-m depth of the surrounding seabed. This topographic high is the southern edge of a large topographic feature identified by Chadwick et al. (2005) as a "constructional ridge," which is estimated to be older than the main volcanic feature of Anatahan. The second topographic high, northeast of Anatahan, is part of a satellite submarine volcano, named "NE Anatahan" by Chadwick et al. (2005). CRED multibeam data reveal that this volcano rises to a depth of 575 m on its crater rim. An area of bumpy topography between Anatahan and NE Anatahan, which is visible on the CRED multibeam (Fig. 9.3.1a, top panel), has been classified by Chadwick et al. (2005) as "volcanic cones overlying eruptive vents." These cones and vent features continue around to the area southeast of Anatahan. Additional volcanic cones are visible in the multibeam bathymetry in deep (1700–2000 m) waters north of Anatahan and west of the large constructional ridge. The low-resolution multibeam bathymetry data obtained by CRED also reveal ridges north and south of Anatahan.

The low-resolution backscatter data collected around Anatahan by CRED also highlight some of the same topographic features. The crater rim of NE Anatahan, for example, is characterized by high backscatter values, supporting the classification by Chadwick et al. (2005) of the rim as "bedrock outcrops." Semicircles of high-intensity backscatter are recorded between Anatahan and NE Anatahan, marking the edges of the volcanic cones mapped by Chadwick et al. (2005). The ridges that shown in the multibeam bathymetry north and south of Anatahan, despite not having distinctly different backscatter intensity from the surrounding seabed, are identified by Chadwick et al. (2005) as "bedrock ridges." In general, backscatter intensity appears fairly uniform, supporting the conclusion by Chadwick et al. (2005) that the majority of the flanks of Anatahan are covered with smooth, volcaniclastic aprons composed primarily of fragments of volcanic debris.

9.3.2 Optical Validation

During MARAMP 2003, 5 TOAD optical-validation surveys, covering a distance of 1.07 km, were conducted around Anatahan (Fig. 9.3.3a). Surveys were conducted in depths of ~ 25 m to > 100 m, although lack of underlying bathymetry data and unreliable depth readings from the TOAD system mean it is not possible to obtain exact depths for these surveys. Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live coral cover.

Covering a distance of 21 km in depths of 4–22 m, 12 towed-diver optical-validation surveys of forereef habitats, were conducted around Anatahan during MARAMP 2003. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover and habitat complexity using a 6-level categorical scale from low to very high.

9.3.3 Habitat Characterization

Sand cover, habitat complexity, and live-hard-coral cover around Anatahan are discussed in this section. MARAMP 2003 surveys were conducted around Anatahan in September, ~ 4 months after a period of major volcanic activity that began in May 2003. Towed-diver surveys and analyses of TOAD video footage suggested predominantly sandy substrates supporting very low levels of live coral cover. Towed divers observed ash covering benthic habitat in most surveys.

North and northeast of Anatahan, towed-diver surveys recorded sand cover of 50.1%–100% (Fig. 9.3.3a) over habitats of low to medium complexity (Fig. 9.3.3b). Analyses of video obtained from the 3 TOAD surveys conducted in this same area suggest a seabed with no sand (Fig. 9.3.3a); however, understand that substrate cover was recorded as "unconsolidated" and not differentiated further because of the difficulty of distinguishing between sand and other soft sediments from video imagery alone. Live coral cover from towed-diver surveys was < 20%, and no hard corals were observed in any of the analyzed TOAD video frames (Fig. 9.3.3c); however, 6 video frames recorded north of Anatahan suggested the presence of non-hard corals. North of Anatahan, habitats including sand-flats and reefs were observed during towed-diver surveys.

Apart from one bay in the western part of the south region, south and southeast of Anatahan, sand cover from towed-diver surveys was generally lower than it was north and northeast of this island, with cover primarily < 50%. Towed-diver surveys suggested locally variable live coral cover, within a range of 1.1%–30%. The highest level of habitat complexity was

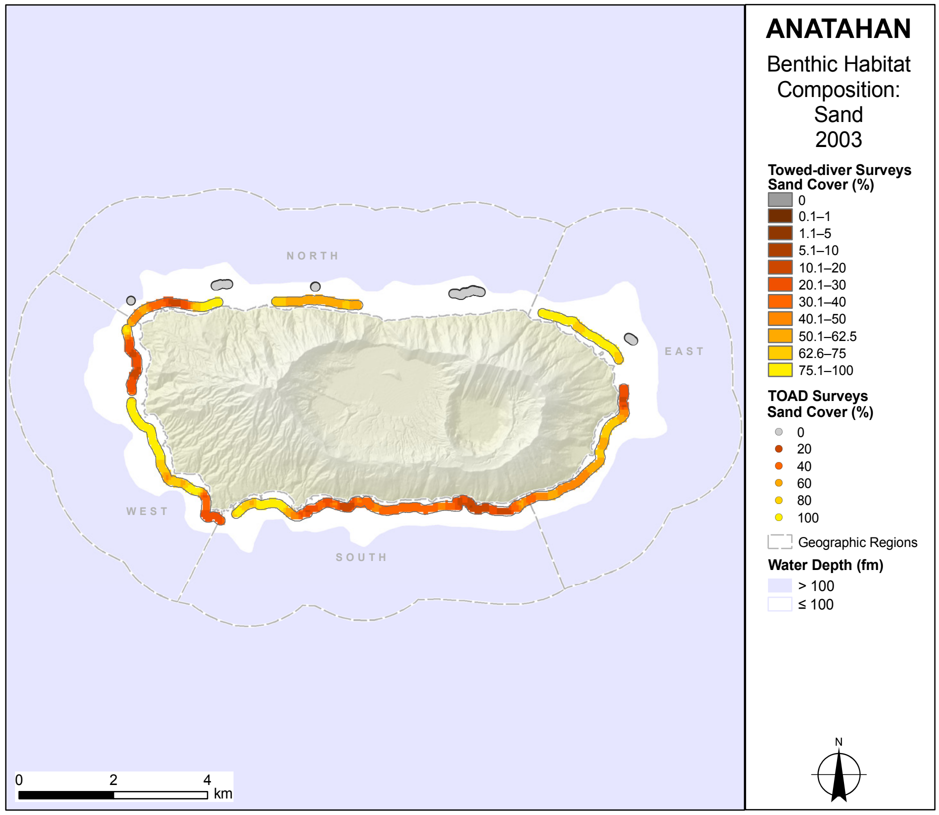


Figure 9.3.3a. Observations of sand cover (%) from towed-diver surveys of forereef habitats conducted and analyses of TOAD video collected around Anatahan during MARAMP 2003.

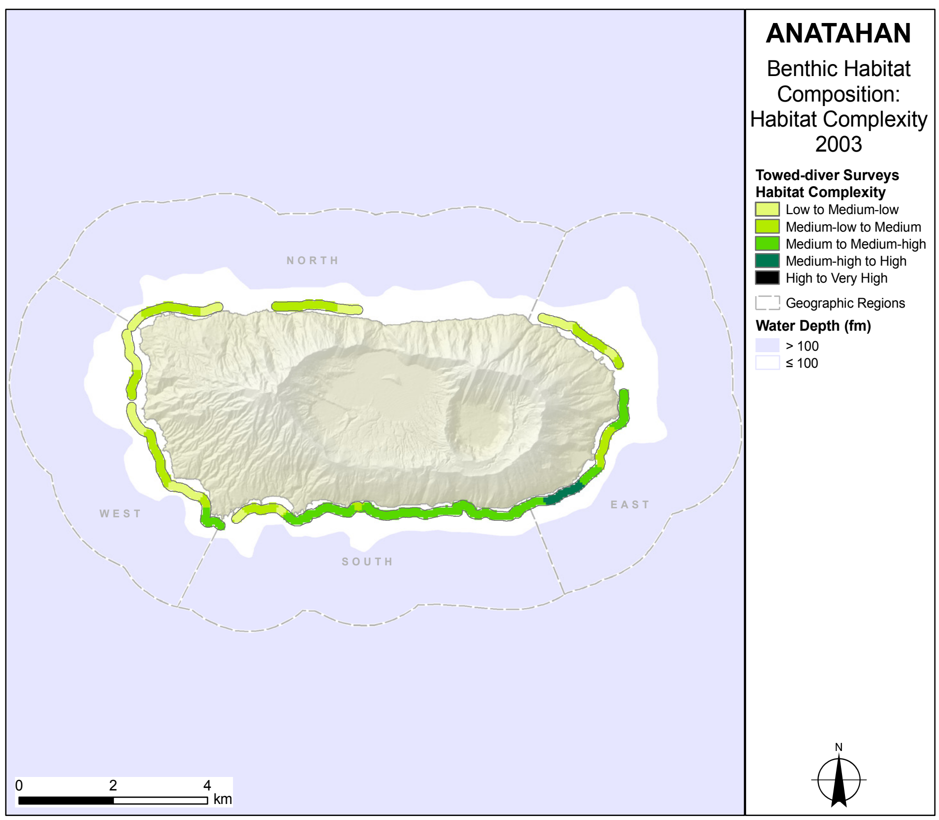


Figure 9.3.3b. Observations of benthic habitat complexity from towed-diver surveys of forereef habitats conducted around Anatahan during MARAMP 2003.

observed in the southern part of the east region, where medium to medium-high complexity was recorded within a small section of 1 survey. The habitat encountered was classified as sand-flats with boulders during towed-diver surveys.

The west region of Anatahan was characterized as soft-sediment habitats with sand cover of 20.1%–100%, based on towed-diver surveys. The habitat here had sand-flats with boulders but with relatively high sand components compared to other parts of this island, suggesting that sand was the dominant substrate. The lowest values of live coral cover at Anatahan, based on towed-diver surveys, consistently were recorded in this region with live coral cover < 5%.

At the northwestern point of this island, some of the highest levels of live coral cover for Anatahan, within a range of 5.1%–30%, were documented during towed-diver surveys. As in other areas around Anatahan, soft sediments dominated habitat observations, and sand cover of 10.1%–100% was recorded during towed-diver surveys. A very short TOAD survey was completed in this area, but only 2 video frames were analyzed. Analyses of both of these frames suggested that the substrate was rock, but it was not possible to classify any benthic fauna from this video footage.

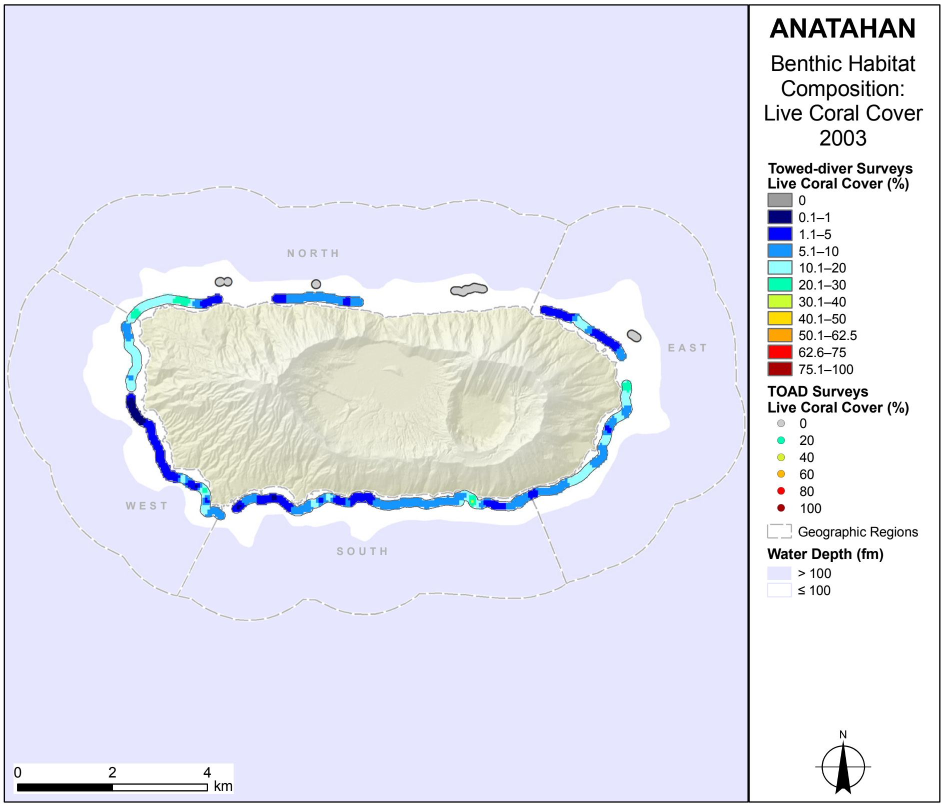


Figure 9.3.3c. Cover (%) observations of live hard corals from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Anatahan during MARAMP 2003.

9.4 Oceanography and Water Quality

9.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, 25 shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around Anatahan on September 10. Temperature, salinity, and density values varied both spatially and vertically. Spatial comparisons of water properties at a depth of 10 m suggest a moderate range in temperature (0.66°C), salinity (0.18 psu), and density (0.37 kg m^{-3}) values around Anatahan. The warmest temperature and lowest salinity values were found in the south region, while cooler and more saline waters were recorded in the east region (Fig. 9.4.1a). Vertical comparisons of CTD profiles reveal strong variability in stratification around this island: well-mixed, warm waters were observed around most of this island with the exception of the east region (casts 12–17), where substantial differences of 3.9°C and 0.7 psu were recorded in temperature and salinity values (Fig. 9.4.1b). This large variation in temperature values likely resulted from upwelling of cold, subsurface waters; however, it is difficult to discern from available data the physical mechanism behind this change.

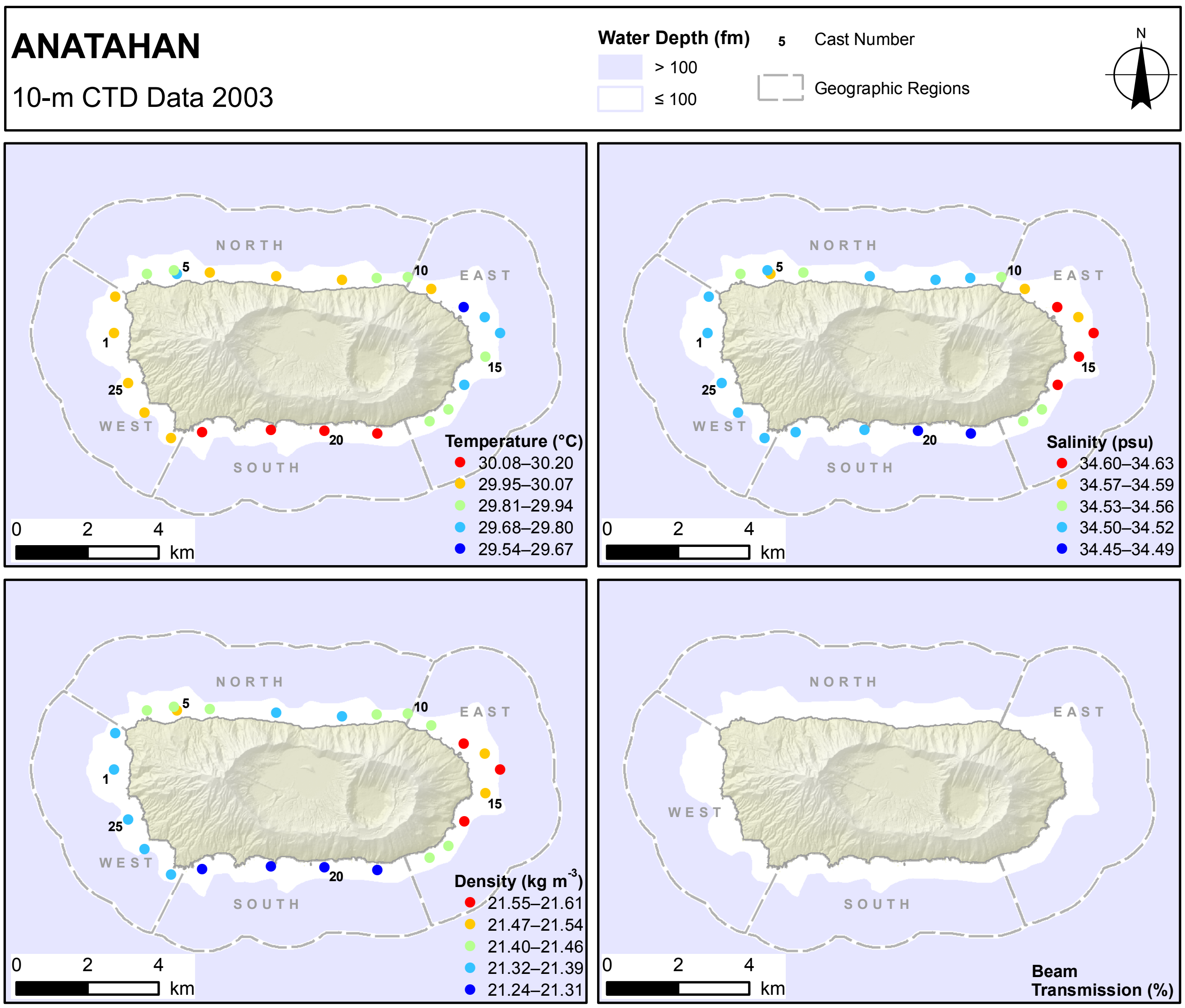


Figure 9.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts around Anatahan on September 10 during MARAMP 2003.

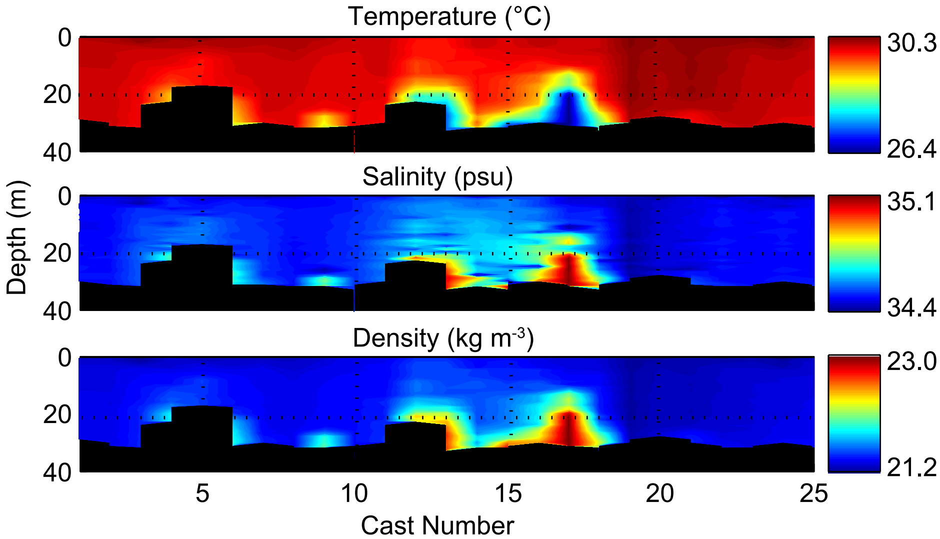


Figure 9.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Anatahan on September 10 during MARAMP 2003, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–25 in a clockwise direction around Anatahan. For cast locations and numbers around this island in 2003, see Figure 9.4.1a.

2005 Spatial Surveys

Eruptions and other volcanic activity prior to MARAMP 2005 sent ash and debris into the nearshore waters, affecting the surrounding environment and limiting the extent of hydrographic data collected during this survey period. On September 23, 2005, 3 shallow-water CTD casts were conducted at Anatahan. Temperature, salinity, and density values varied both spatially and vertically. Spatial comparisons of water properties at a depth of 10 m suggest moderate ranges in temperature (0.96°C), salinity (0.17 psu), and density (0.49 kg m^{-3}) values (Fig. 9.4.1c). Vertical comparisons of CTD profiles reveal water properties with large differences in temperature (1.6°C), salinity (0.4 psu), and density (0.8 kg m^{-3}) values (Fig. 9.4.1d).

Water samples were collected in concert with the 3 shallow-water CTD casts conducted at Anatahan in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.163–0.187 µg L^{-1}; total nitrogen (TN), 0.063–0.075 µM; nitrate (NO_3^-), 0.032–0.057 µM; nitrite (NO_2^-), 0.008–0.031 µM; phosphate (PO_4^{3-}), 0.027–0.092 µM; and silicate [$Si(OH_4)$], 0.567–1.206 µM. Based on data from the 3 sample locations, Chl-*a*, phosphate, silicate, and nitrite values were highest in the west region (Fig. 9.4.1e), where temperature values were also greatest.

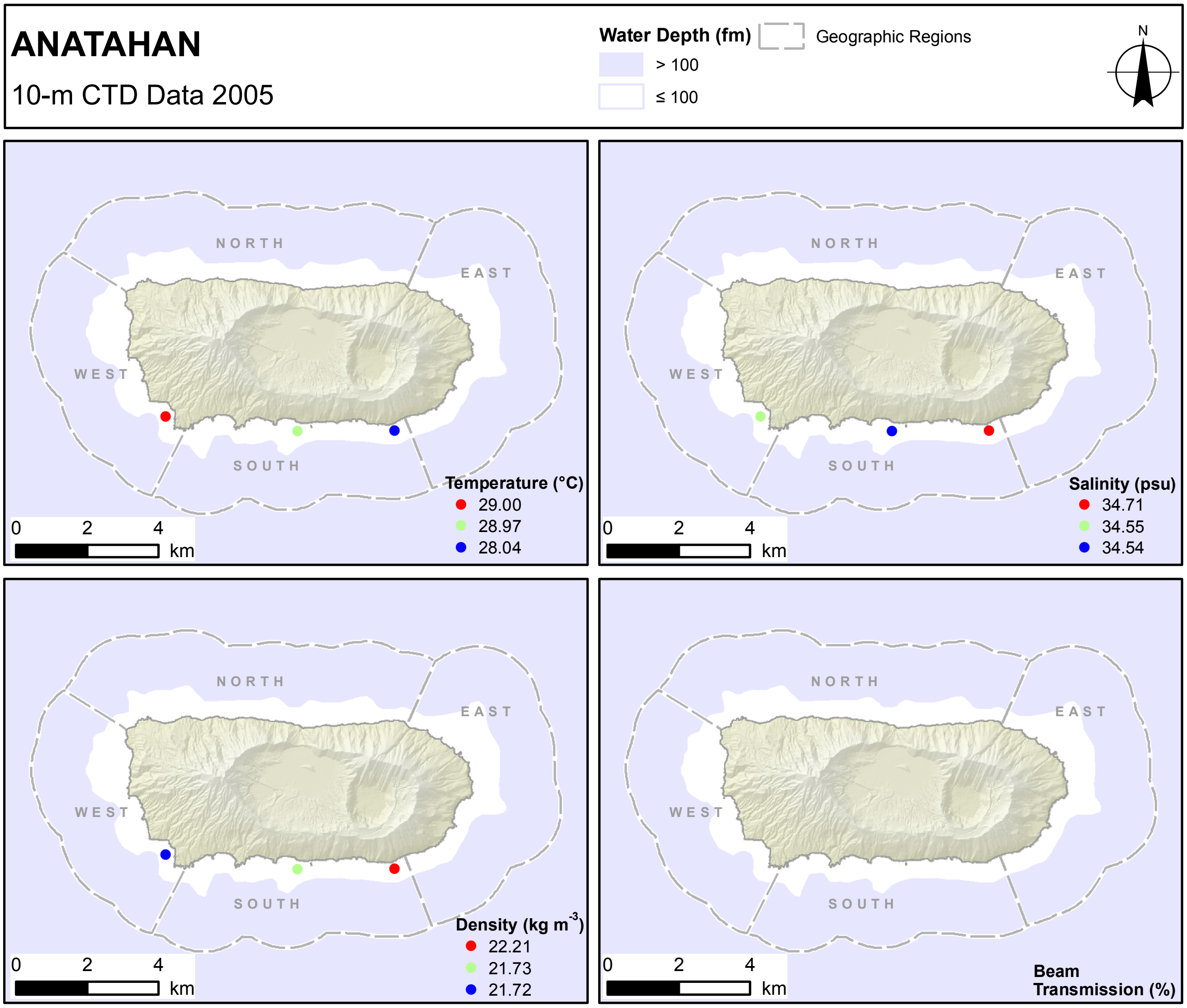
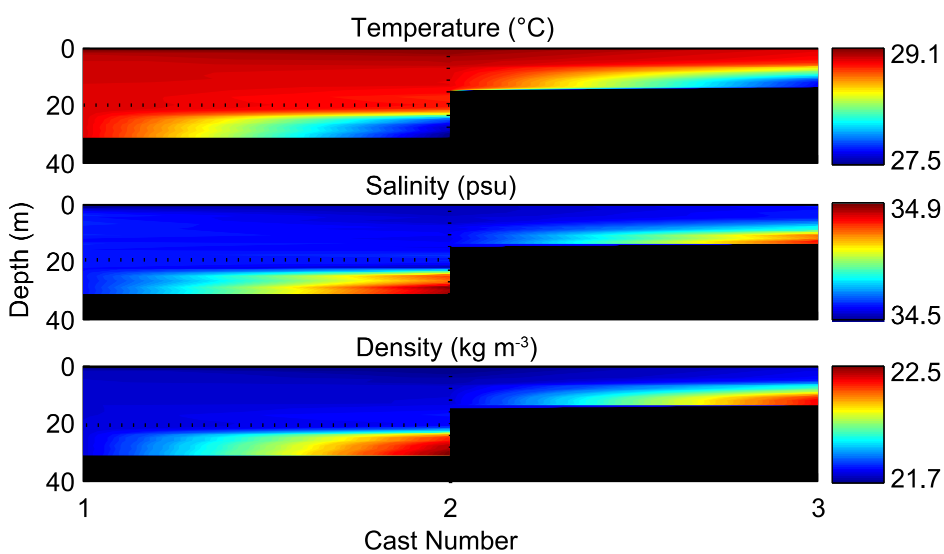


Figure 9.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, and (*bottom left*) density at a 10-m depth from shallow-water CTD casts conducted at Anatahan on September 23 during MARAMP 2005.

Figure 9.4.1d. Shallow-water CTD cast profiles to a 30-m depth at Anatahan on September 23 during MARAMP 2005, including temperature (°C), salinity (psu), and density (kg m^{-3}). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations shown in Figure 9.4.1c.



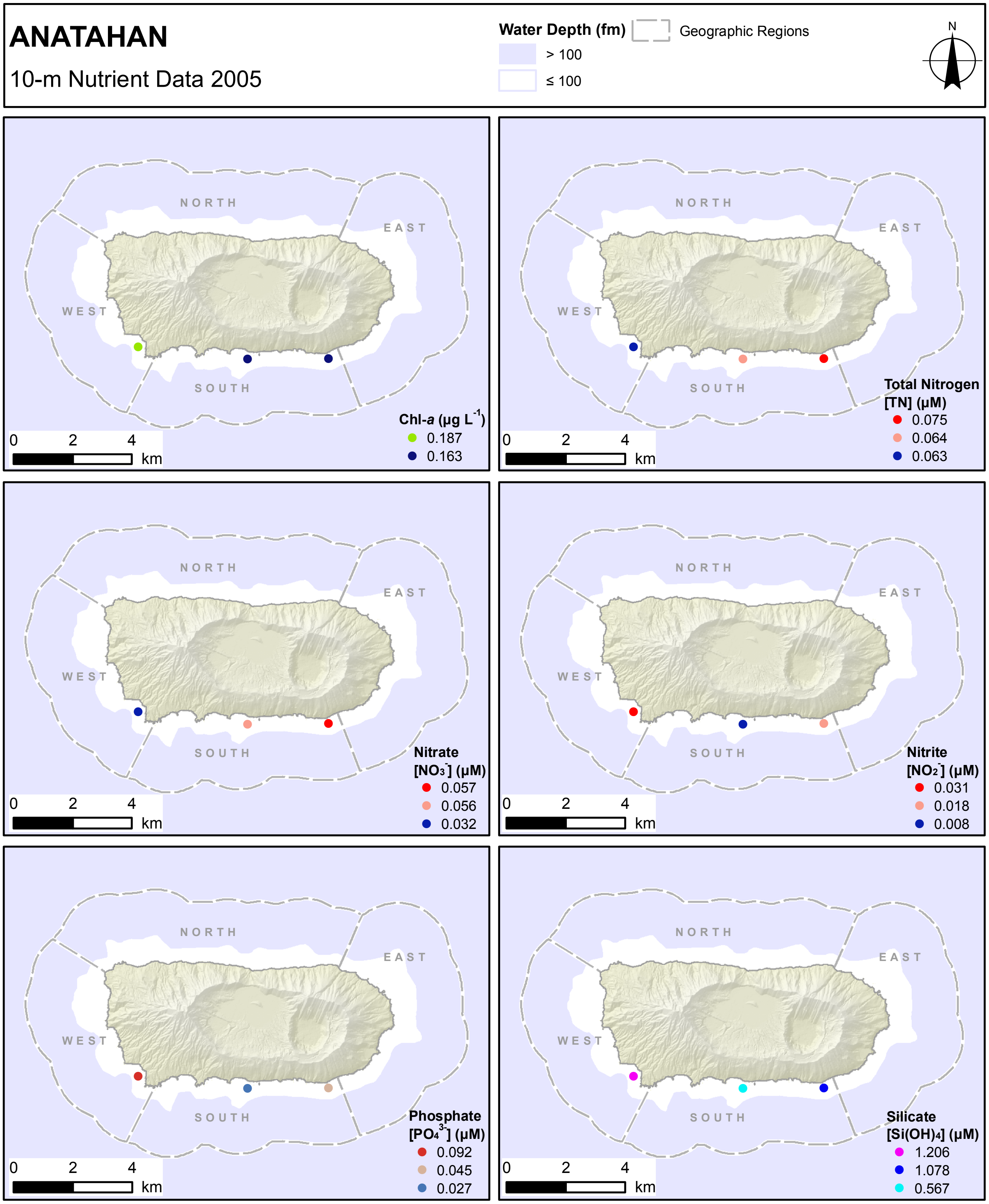


Figure 9.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected at Anatahan on September 23 during MARAMP 2005.

2007 Spatial Surveys

Eruptions and other volcanic activity prior to MARAMP 2007 sent ash and debris into the nearshore waters, affecting the surrounding environment and limiting the extent of hydrographic data collectedduring this survey period. On May 27, 2007, 3 shallow-water CTD casts were conducted in the south region. Spaital comparisons of water properties at a depth of 10 m suggest small ranges in temperature (0.18°C), salinity (0.04 psu), and density (0.08kg m^{-3}), and beam transmission (0.04%) values (Fig. 9.4.1f). Beam transmission was low (~ 91%) for this geographic region, compared to results from other locations surveyed in the Mariana Archipelago. Vertical comparisons of CTD profiles (Fig. 9.4.1g) revealed a stratified water column with highly turbid waters recorded at depths of 5–10 m, likely a result of ash and other debris from the recent volcanic eruption. A moderate range in temperature (0.7°C) values and small ranges in salinity (0.1 psu), density (0.3 kg m^{-3}), and beam transmission (1.5%) values were recorded.

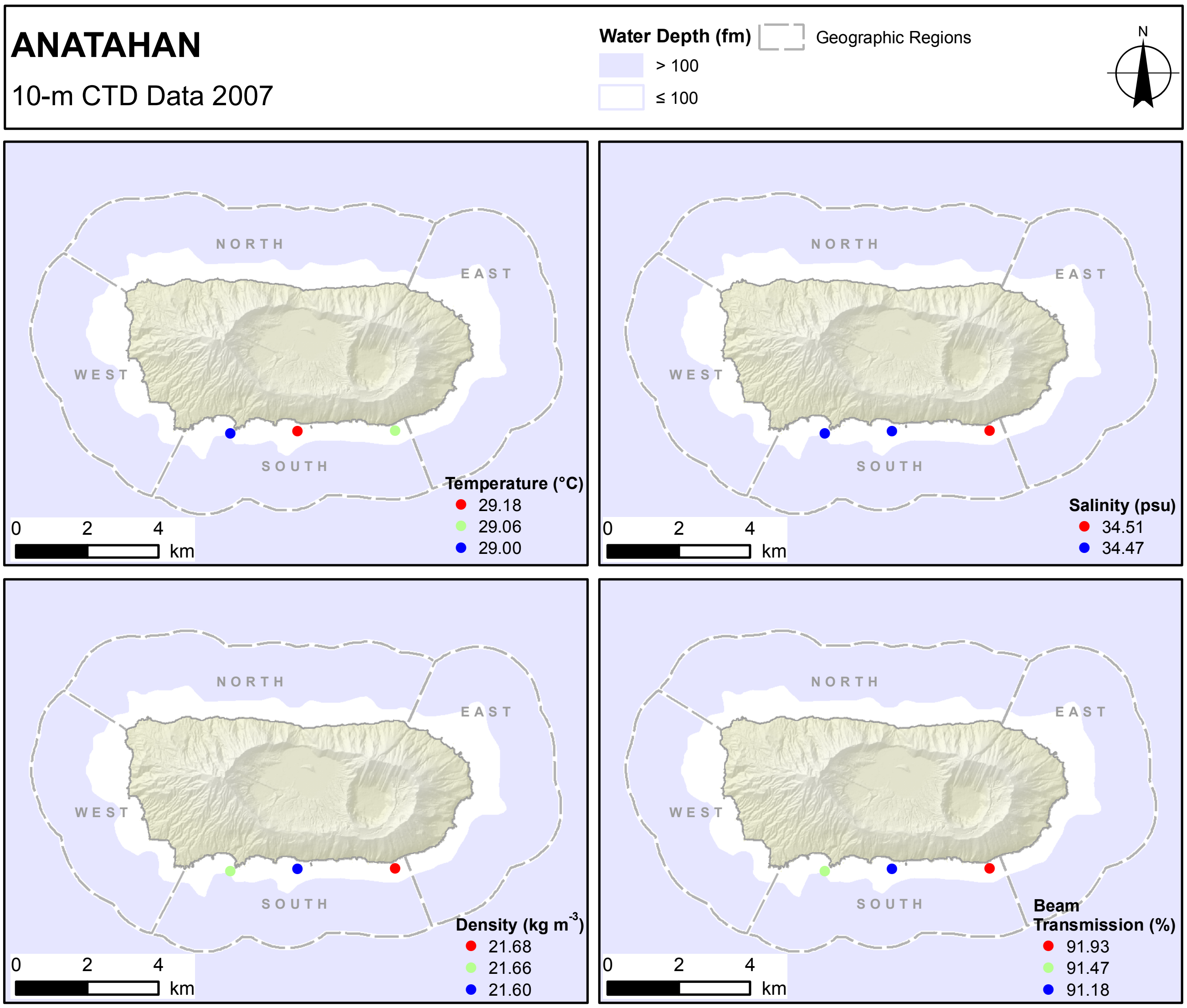


Figure 9.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts conducted at Anatahan on May 27 during MARAMP 2007.

Water samples were collected in concert with a shallow-water cast at 1 select location at Anatahan in 2007 to assess water-quality conditions. The following values of measured parameters were recorded: Chl-*a*, 0.08 µg L^{-1}; total nitrogen (TN), 0.027 µM; nitrate (NO^{3-}), 0.024 µM; nitrite (NO^{2-}), 0.003 µM; phosphate ($PO4^{3-}$), 0.040 µM; and silicate [$Si(OH)_4$], 1.321 µM (Fig. 9.4.1h).

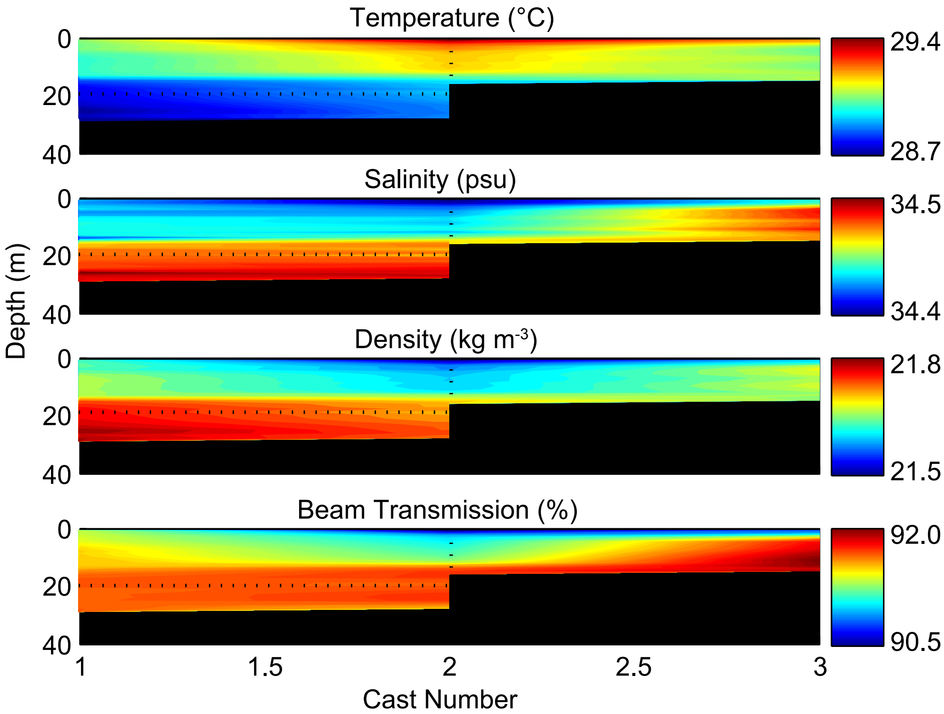


Figure 9.4.1g. Shallow-water CTD cast profiles to a 30-m depth at Anatahan on May 27 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations in the south region shown in Figure 9.4.1f.

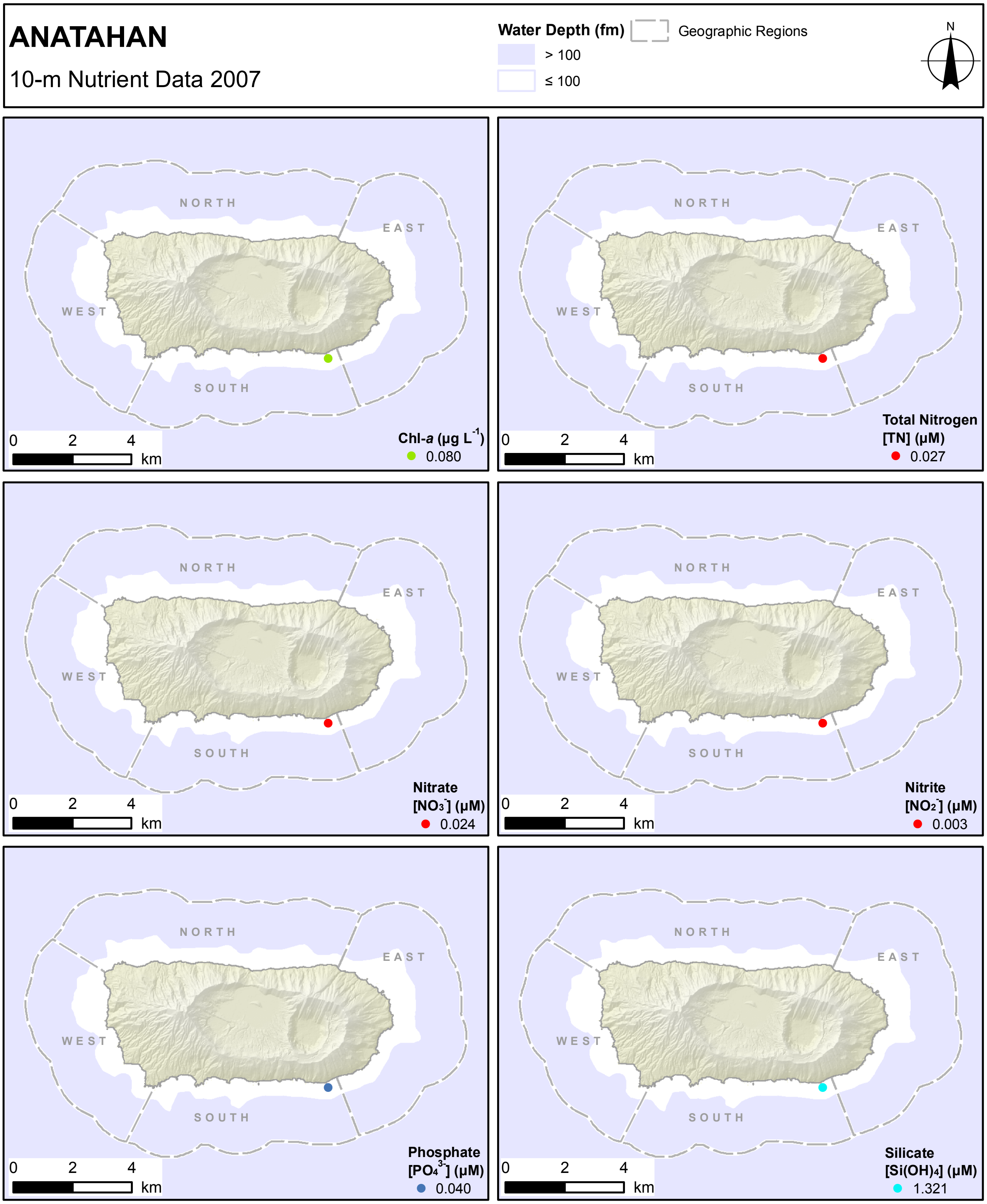


Figure 9.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate, at a 10-m depth from water samples collected at a single cast location at Anatahan on May 27 during MARAMP 2007.

Temporal Comparison

Given the lack of hydrographic data collected during MARAMP 2005 and 2007 and with the seasonal difference in sampling (MARAMP 2007 occurred in May, while MARAMP 2003 and 2005 occurred in September), it is not possible to make meaningful interannual comparisons of oceanographic conditions at Anatahan.

9.4.2 Time-series Observations

Between 2003 and 2007, subsurface temperature recorders (STRs) were deployed at Anatahan to collect time-series observations of temperature, a key oceanographic parameter influencing reef conditions (Fig. 9.4.2a). The location, depth, and time frame of the deployments at Anatahan are provided in Figures 9.4.2a and b.

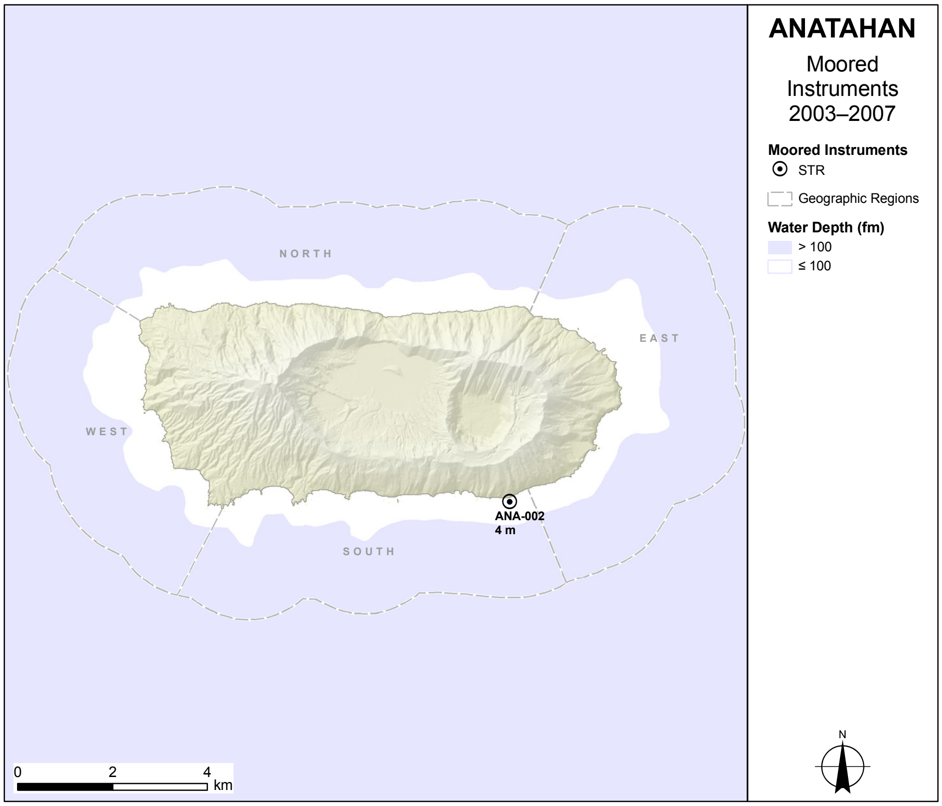


Figure 9.4.2a. Location and depth of STRs deployed at Anatahan during MARAMP 2003, 2005, and 2007.

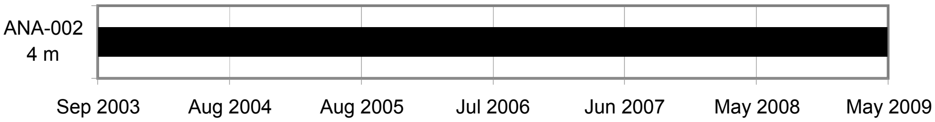


Figure 9.4.2b. Deployment timeline and depth of the STRs moored at Anatahan during the period from September 2003 to May 2009. A solid bar indicates the period for which temperature data were collected by a series of STRs deployed and retrieved at mooring site ANA-002. For more information about deployments and retrievals, see Table 9.2b in Section 9.2: "Survey Effort."

Temperature data collected by STRs deployed at a depth of 4 m in the south region show seasonal temperature variability of ~ 3°C between summer and winter months (Fig. 9.4.2c) Water temperatures reached ~ 30.5°C during the months of June–October and fell to a low of ~ 27°C from January–May. Superimposed on this seasonal temperature variability were frequent intraseasonal fluctuations. Temperature values, for example, dropped nearly 3°C in July 2004 for ~ 2 weeks before sharply increasing to typical summertime temperatures. Sharp decreases in temperature also were observed in September 2004 and summer 2005. Temperatures in September 2006 reached the coral bleaching threshold, defined as 1°C above the monthly maximum climatological mean.

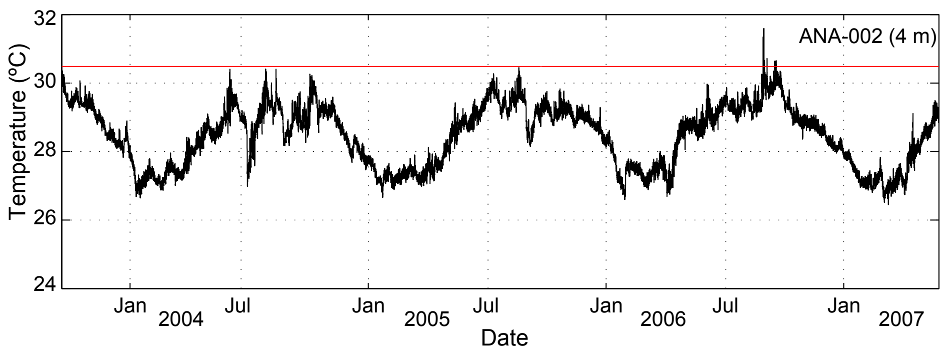


Figure 9.4.2c. Time-series observations of temperature over the period between September 2003 and July 2007 collected from 1 STR mooring site (ANA-002) in the south region at a 4-m depth at Anatahan (see Figure 9.4.2a for mooring location). The red line indicates the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

9.4.3 Wave Watch III Climatology

Seasonal wave climatology for Anatahan was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008 (Fig 9.4.3a), and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: "Methods and Operational Background," Section 2.3.7: "Satellite Remote Sensing and Ocean Modeling"). In terms of consistency, the wave regime during this period was dominated by trade wind swells, characterized by frequent (> 30 d per season), short-period (8–10 s), relatively small (2–2.5 m) wave events originating from the east (~ 80°–90°). Superimposed on these short-period swells were large (> 5 m), long-period (12–16 s) wave events from the southeast–southwest (130°–210°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–4.0 m) could occur from any direction, although weighted slightly larger from the south (130°–260°), and likely were associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) also was characterized by frequent (> 30 d per season), short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 5 d per season), long-period (12–14 s) swells with slightly larger wave heights (~ 2–3 m) also occurred during this period and could originate from any direction.

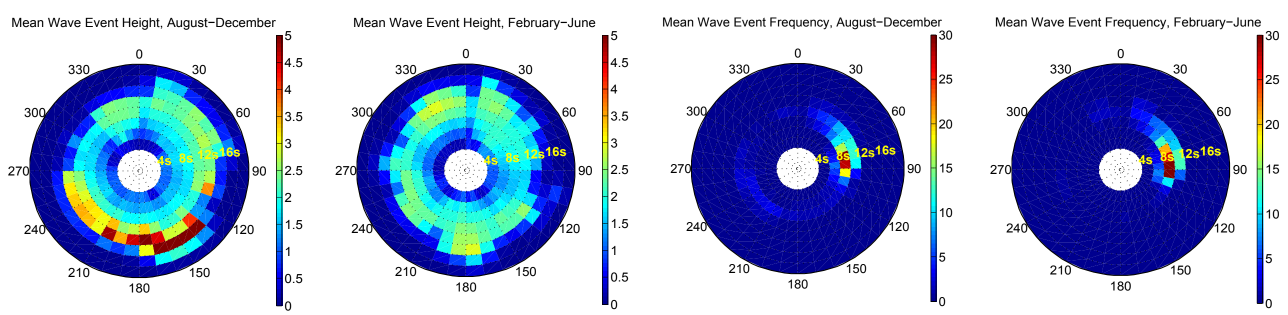


Figure 9.4.3a. NOAA Wave Watch III directional wave climatology for Anatahan from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Anatahan (16° N, 145° E). Mean significant wave height (*far left and left*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*right and far right*) that conditions in each directional and frequency bin occurred in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 of the 150 days of that season.

9.5 Corals and Coral Disease

9.5.1 Coral Surveys

Anatahan volcano erupted on May 10, 2003, sending a massive column of volcanic ash and gas > 10 km above sea level. Falling ash buried parts of this island in a layer more than 45 cm thick, and traveled west from Anatahan in prevailing winds. Heavy ash settled on the coasts of this island, particularly in the north and west regions, covered coral reefs, and greatly altered light penetration and reef conditions. Because low-level volcanic activity continued during the MARAMP survey periods, REA and towed-diver surveys of corals were not completed at Anatahan in 2005 or 2007. In those years, getting near this island was dangerous, and the large amount of volcanic ash in the water column reduced visibility to close to zero.

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats for the island of Anatahan was 8% (SE 0.6). Coral cover was relatively low along all forereef areas surveyed around Anatahan, compared to other survey areas in the Mariana Archipelago. Localized areas of high coral cover, within a range of 20.1%–30%, were observed around this island's easternmost point over 1 segment, in the western part of the north region over 3 segments, and the southwestern part of the west region over 1 segment (Fig. 9.5.1a). An additional area of high coral cover, within a range of 20.1%–40%, was recorded in the south region over 2 segments. Observations of recently dead corals and diversity of dead coral skeletons, made during towed-diver surveys, suggested that reefs north of Anatahan may have been extensive prior to the eruption in 2003.

During MARAMP 2003, 5 REA benthic surveys using the quadrat method on forereef habitats at Anatahan documented 408 coral colonies within a total survey area of 18.75 m^2. Site-specific colony density ranged from 10.7 to 34.4 colonies m^{-2} with an overall sample mean of 21.8 colonies m^{-2} (SE 4.4). The highest colony density was recorded at REA site ANA-05 in the south region, and the lowest colony density was observed in the west region at ANA-03 (Fig. 9.5.1b).

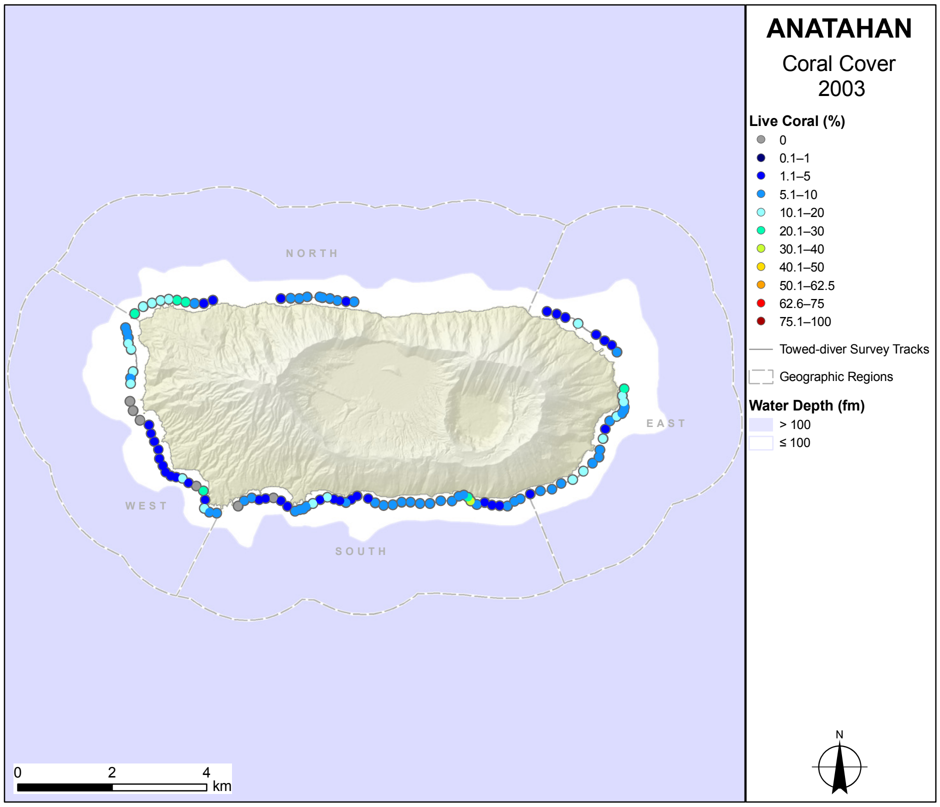


Figure 9.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 m x 10 m (~ 2000 m^2).

Figure 9.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Anatahan during MARAMP 2003. Values are provided within or above each symbol. The quadrat method was used in 2003 to assess coral-colony density.

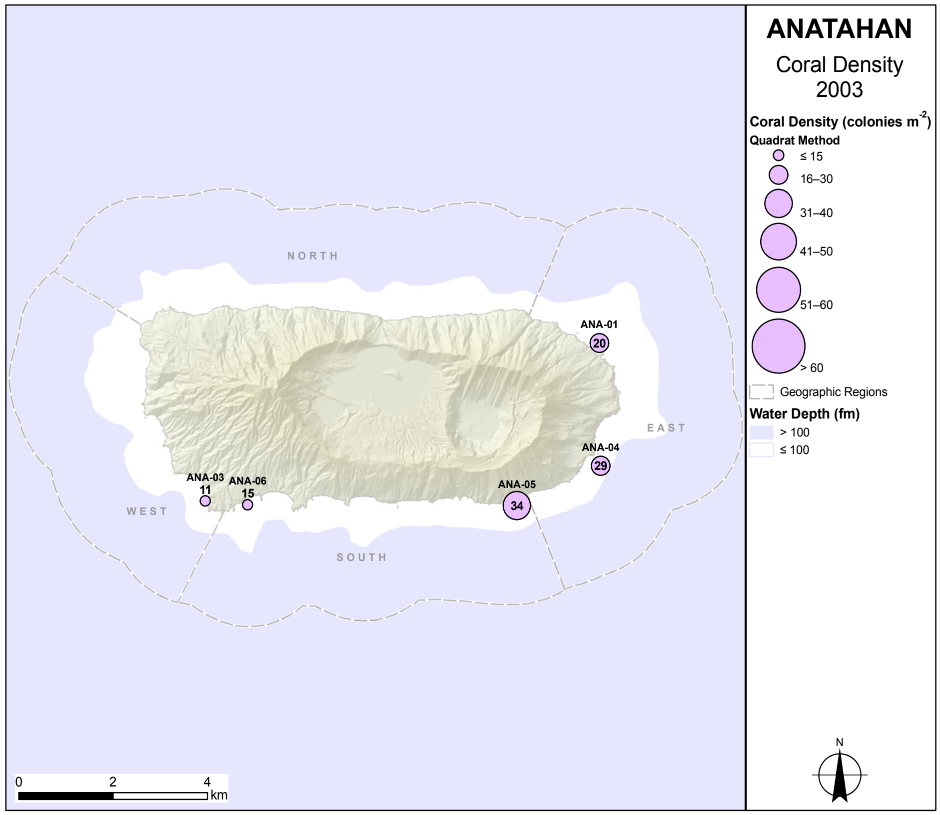
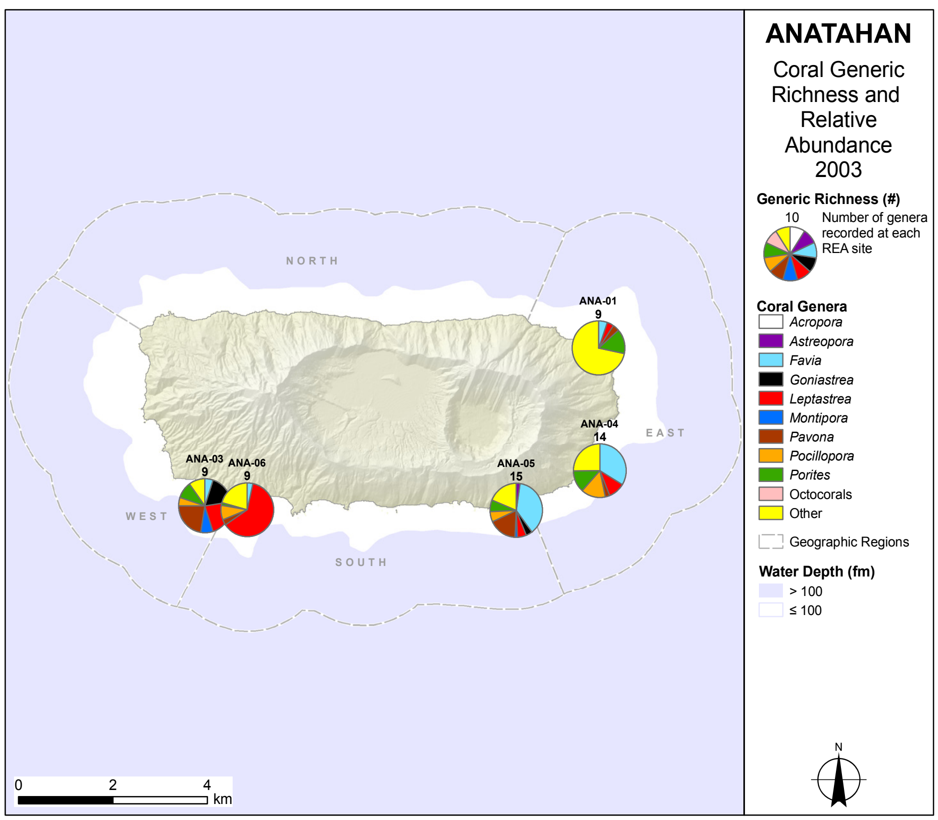


Figure 9.5.1c. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Anatahan during MARAMP 2003. The pie charts indicate the percentages of relative abundance of key coral genera. The quadrat method was used in 2003 to survey coral genera.



Coral Generic Richness and Relative Abundance

Five REA benthic surveys of forereef habitats were conducted using the quadrat method at Anatahan during MARAMP 2003. During this survey period, 20 coral genera were observed at Anatahan. Generic richness ranged from 9 to 15 with a mean of 11.2 (SE 1.4) coral genera per site and 20 genera observed overall at Anatahan. The highest generic diversity was seen at ANA-05 in the south region, and the lowest generic diversity was recorded at 3 sites: ANA-01, ANA-03, and ANA-06 in the east, west, and south regions (Fig. 9.5.1c).

Leptastrea, *Favia* and *Pavona* were the most numerically abundant genera, contributing 20.8%, 16.9%, and 10% of the total number of colonies enumerated at Anatahan in 2003. All other genera individually contributed < 10% of the total number of colonies. *Leptastrea* and *Pavona* dominated the coral fauna at ANA-03 in the west region, each contributing 22.5% of the total number of colonies at this site. *Leptastrea* was the most abundant genus at ANA-06 in the south region, contributing 62.1% of the total number of colonies at this site. *Favia* dominated the coral fauna at ANA-04 and ANA-05 in the east and south regions, accounting for 33.3% and 37.2% of the total number of colonies at these sites. *Montastrea* dominated the coral fauna at ANA-01 in the east region, contributing 50% of the total number of colonies at this site.

Coral Size-class Distribution

During MARAMP 2003, 5 REA benthic surveys of forereef habitats were conducted at Anatahan using the quadrat method. The coral size-class distributions from these surveys show that the majority (75.4%) of corals had maximum diameters ≤ 5 cm (Figs. 9.5.1d and e). The next 3 size classes (6–10, 11–20, and 21–40 cm) accounted for 17.6%, 5.3%, and 1.8% of colonies recorded. No colonies with maximum diameter > 40 cm were observed. At each REA site, a majority (> 60%) of corals were in the smallest size class (0–5 cm).

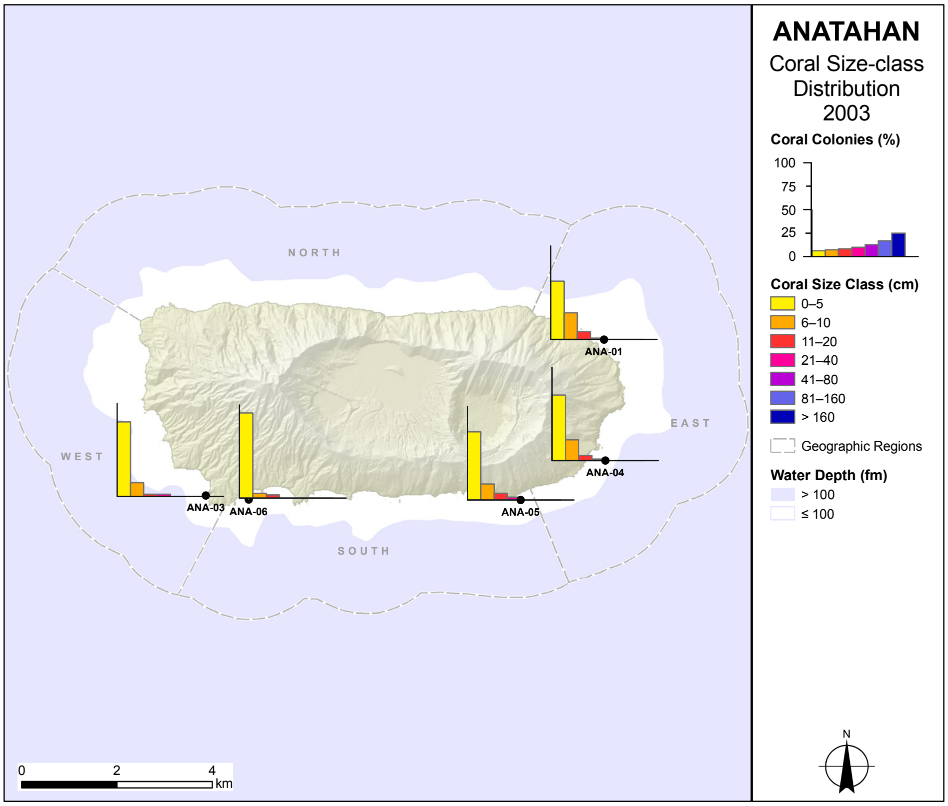


Figure 9.5.1d. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Anatahan during MARAMP 2003. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 to size corals.

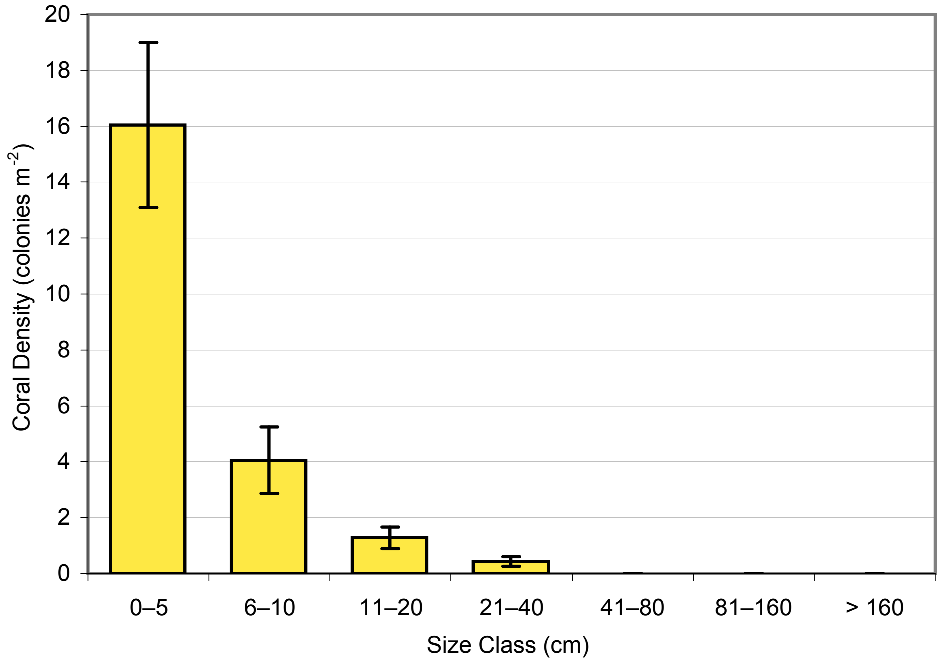


Figure 9.5.1e. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Anatahan during MARAMP 2003. The quadrat method was used in 2003 to size corals. Error bars indicate standard error (± 1 SE) of the mean.

9.5.2 Coral-disease Surveys

Anatahan was not surveyed for coral disease and predation during MARAMP 2003, 2005, and 2007.

9.6 Algae and Algal Diseases

9.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

Towed-diver surveys at Anatahan were completed in September 2003, when large amounts of ash were frequently seen on reefs or in the water column. For example, during a survey in the southern part of the west region, divers reported that everything on the seafloor appeared “dead” for the entire length of this survey. Such observations make it apparent that the coral reef ecosystem at Anatahan had already suffered significant effects from the volcanic eruptions that began in May 2003.

From MARAMP 2003 towed-diver surveys, mean macroalgal cover around the island of Anatahan was 14% (SE 1.6) (Fig. 9.6.1a). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 48%, within a range of 0%–75%, occurred in the northern part of the west region (Fig. 9.6.1b, left panel). Habitat in this area primarily was composed of low-relief pavement of low complexity. The second-and third-greatest levels of macroalgal cover, with means of 34% and 30%, were observed during the 2 surveys completed in the southern part of the east region. Habitats observed during these surveys mostly had rock boulders and were characterized as medium and medium-high complexity. All other surveys conducted in 2003 recorded macroalgal cover ≤ 6%.

TOAD surveys completed in the north and east regions of Anahatan during MARAMP 2003 were conducted at depths of 1–100 m. Based on analyses of TOAD video footage obtained from the 5 completed surveys, the observed seabed had no macroalgae and was primarily composed of unconsolidated sediment, such as volcanic ash (Fig. 9.6.1b, left panel).

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Anatahan was 8% (SE 0.7; Fig. 9.6.1a). The survey with the highest mean crustose-coralline-red-algal cover of 22%, within a range of 5.1%–30%, occurred along the coast in the center of the south region (Fig. 9.6.1b, right panel). Habitat observed during this survey primarily was of medium-high complexity and composed of rock boulders interspersed with pavement. In the west and north regions, 4 surveys recorded the lowest levels of crustose-coralline-red-algal cover with means of 2%–3%. Habitats seen during these surveys primarily were pavement of low to medium-low complexity.

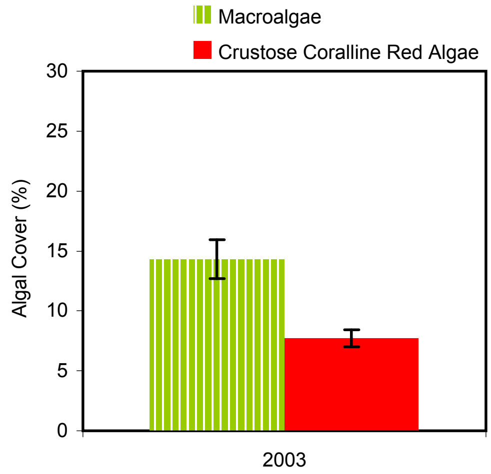


Figure 9.6.1a. Algal cover (%) values for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003. Macroalgal cover includes turf algae in addition to macroalgae. Error bars indicate standard error (± 1 SE) of the mean.

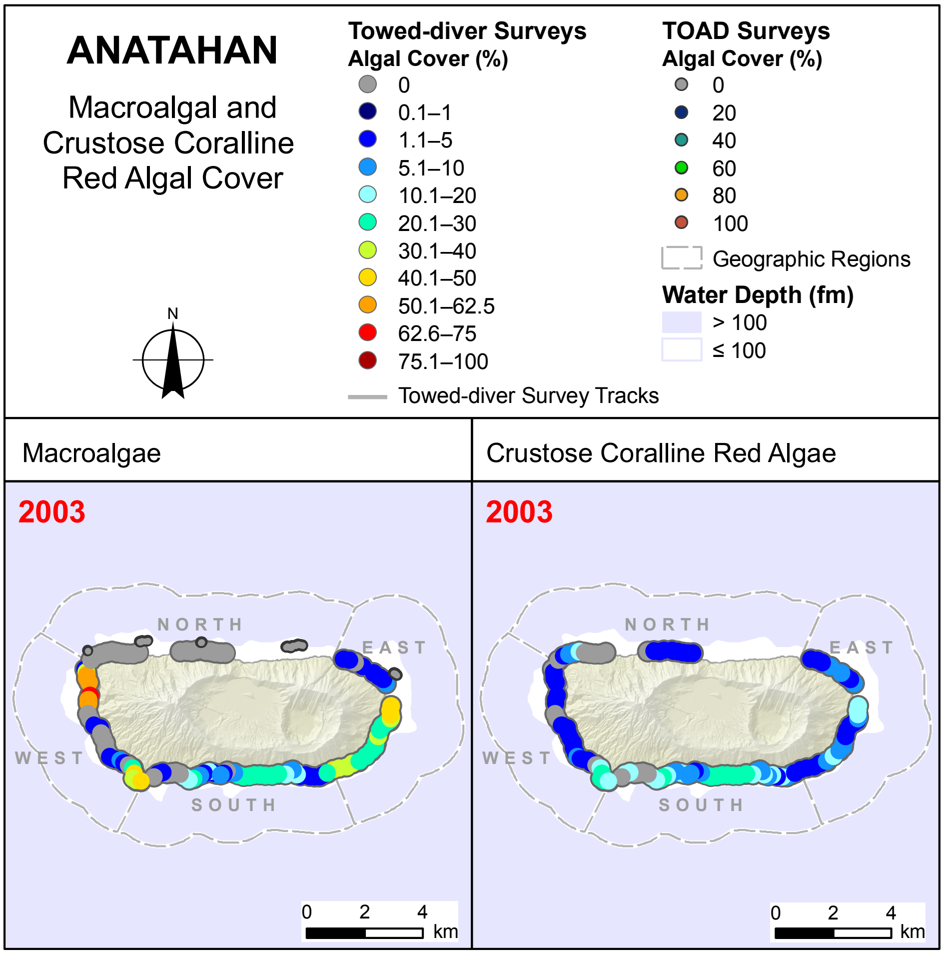


Figure 9.6.1b. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003. Each large, colored point represents an estimate over a 5-min observation segment with a towed-diver survey swath of ~ 200 × 10 m (~ 2000 m^2). The left panel shows observations of both macroalgae and turf algae. In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

Macroalgal Genera and Functional Groups

In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islands of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 4 sites on forereef habitats at Anatahan. In the field, 7 macroalgal genera (4 red, 1 brown, and 2 green), containing at least 7 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanobacteria—were observed. REA site ANA-04 in the east region had the highest macroalgal generic diversity recorded in the field with 6 genera, containing 6 species, documented. The lowest macroalgal generic diversity was found at ANA-06 in the western part of the south region.

Macroalgal cover at Anatahan overall was low compared to results for other islands surveyed in the Mariana Archipelago, likely because of the recent eruption. The most frequently observed genus was the red alga *Jania*, recorded in only 10.4% of the photoquadrats sampled at Anatahan (Figs. 9.6.1c and d). A single species of the calcified, green algal genus *Halimeda* and a single species of the calcified, red algal genus *Peyssonnelia* were each recorded in 8.3% of sampled photoquadrats. Species of the red algal genus *Hypoglossum*, brown algal genus *Lobophora*, and green algal genus *Neomeris*, as well as an unidentified member of the red algal order Gelidiales, were each recorded in < 5% of sampled photoquadrats. Algal biodiversity was much higher along the southeastern coast than along the southwestern coast. Of the 7 genera recorded at Anatahan, all except *Jania* were recorded at ANA-04 in the east region. At this site, *Peyssonnelia* was the most abundant macroalgal genus, although this genus only occurred in 25% of photoquadrats sampled at this site. All other genera found at ANA-04 occurred in < 16.7% of the photoquadrats sampled at this site. At ANA-05, located only 2 km to the west of ANA-04 in the south region, only 3 genera were observed, and species of *Jania* were found in 41.7% of sampled photoquadrats, the highest abundance recorded for this genus at Anatahan. The only algal genus recorded at ANA-03 in the west region was *Lobophora*, found in 8.3% of sampled photoquadrats. No macroalgal genera were observed at ANA-06 in the south region; however, the algal functional groups of turf algae and crustose coralline red algae were seen at this site.

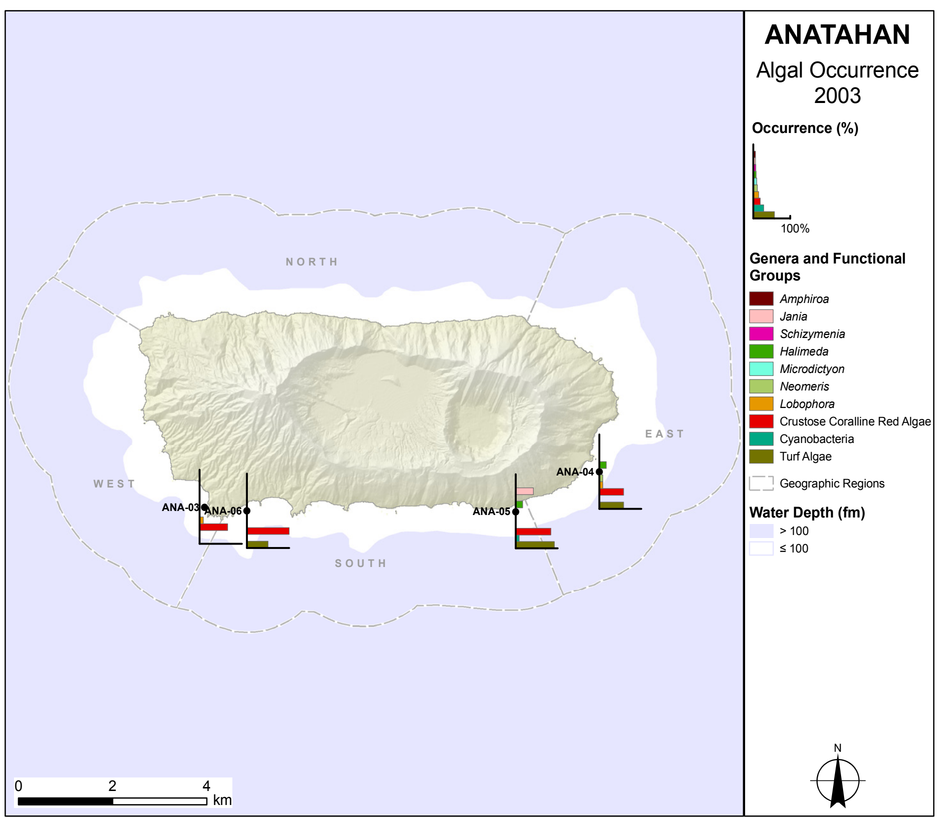


Figure 9.6.1c. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Anatahan during MARAMP 2003. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

Turf algae and crustose coralline red algae were both common in 2003, occurring in 50% and 77.1% of photoquadrats sampled at Anatahan (Figs. 9.6.1c and d). Unusually, turf algae, the main benthic substrate cover in most coral reef ecosystems,were not recorded at all sites surveyed at Anatahan; this functional group was absent from ANA-03, the westernmost site. Turf-algal occurrence at Anatahan appeared proportional to macroalgal occurrence, as this functional group was most abundant when macroalgal occurrence was also highest, with the exception of results from ANA-06, where turf algae were found in 50% of sampled photoquadrats and no macroalgae were recorded. Common at every site surveyed at Anatahan, crustose coralline red algae were the most abundant functional group recorded in the field. Along the southwestern coast, where macroalgal diversity and occurrence were low, crustose coralline red algae were recorded in 100% and 66.7% of photoquadrats sampled at ANA-06 and ANA-03. On reefs along the southeastern coast, where macroalgal diversity was highest, crustose coralline red algae were found in 58.3% and 83.3% of photoquadrats sampled at ANA-04 and ANA-05. Cyanobacteria only occurred in 2.1% of sampled photoquadrats.

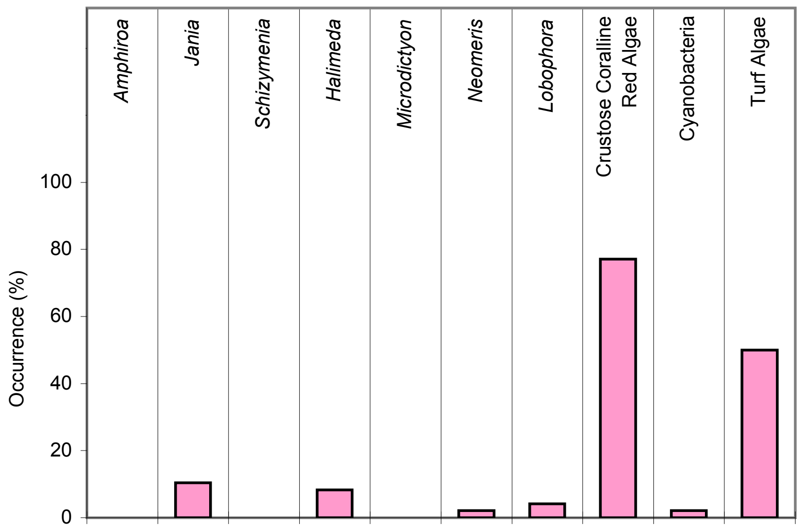


Figure 9.6.1d. Occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Anatahan during MARAMP 2003.

9.6.2 Coralline-algal-disease Surveys

No surveys for coralline-algal disease were conducted at Anatahan during MARAMP 2003, 2005, or 2007.

9.7 Benthic Macroinvertebrates

9.7.1 Benthic Macroinvertebrates Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were surveyed on forereef habitats around the island of Anatahan through benthic REA and towed-diver benthic surveys during MARAMP 2003. This section describes by group the results of these surveys. A list of additional taxa observed during the REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

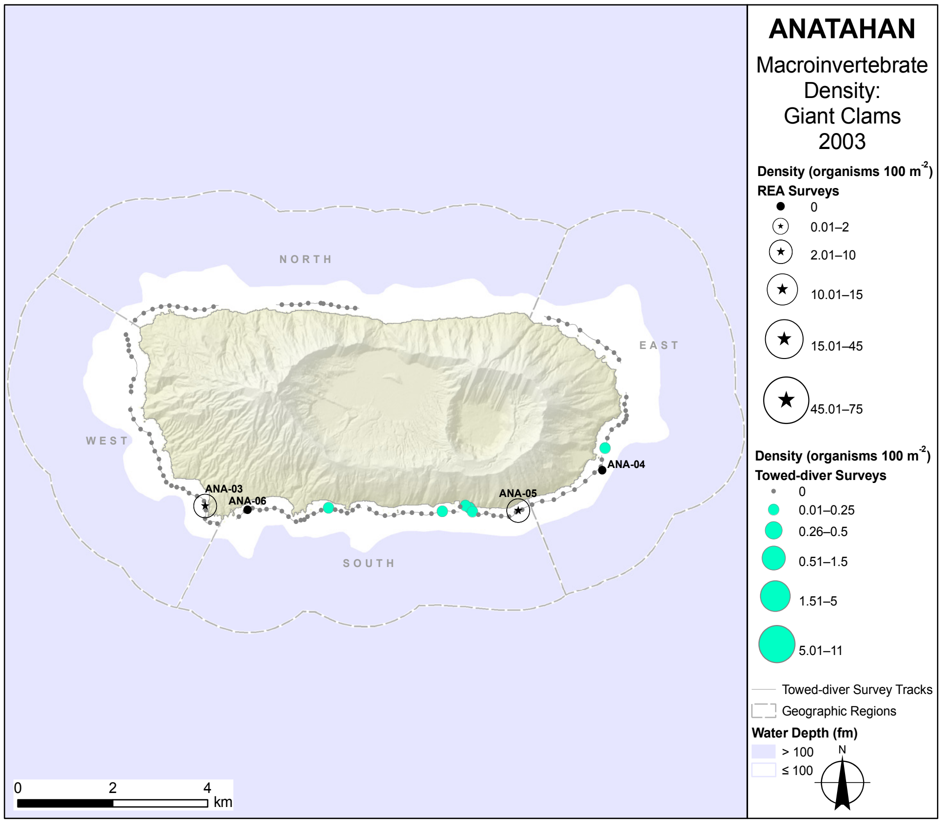
Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 4 REA benthic surveys and 12 towed-diver surveys were conducted. Because low-level volcanic activity continued through 2008, benthic macroinvertebrate surveys were not completed at Anatahan in 2005 or 2007. In those years, getting near this island was dangerous, and the large amount of volcanic ash in the water column made visibility close to zero. The restricted visibility during the MARAMP 2003 towed-diver surveys likely negatively biased estimated densities of macroinvertebrates. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present. Overall, both the REA and towed-diver surveys revealed low daytime abundance of macroinvertebrates on forereef habitats around Anatahan.

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at 2 of the 4 REA sites surveyed and in 4 of the 12 towed-diver surveys conducted around Anatahan. The sample mean density of giant clams from REA surveys was 1.75 organisms 100 m^{-2} (SE 1.03), and the overall mean density from towed-diver surveys was 0.004 organisms 100 m^{-2} (SE 0.002). Survey results suggest that giant clams were most abundant at REA site ANA-05 in the eastern part of the south region with 4 organisms 100 m^{-2} (Fig. 9.7.1a). Among all towed-diver surveys around this island, 2 surveys completed in the south region had the highest mean densities of giant clams with 0.025 and 0.01 organisms 100 m^{-2}; segment densities from these surveys ranged from 0 to 0.102 organisms 100 m^{-2}.

Figure 9.7.1a. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003.



Crown-of-thorns Seastars

During MARAMP 2003, no crown-of-thorns seastars (*Acanthaster planci*) were observed at the 4 REA sites surveyed at Anatahan, but 1 of the 12 towed-diver surveys had recordings of COTS (Fig. 9.7.1b). The COTS density from this towed-diver survey in the south region was 0.001 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.046 organisms 100 m^{-2}.

Sea Cucumbers

During MARAMP in 2003, sea cucumbers were observed at 2 of the 4 REA sites surveyed and in 10 of the 12 towed-diver surveys conducted around Anatahan. The sample mean density of sea cucumbers from REA surveys was 1.5 organisms 100 m^{-2} (SE 1.19), and the overall mean density from towed-diver surveys was 0.1 organisms 100 m^{-2} (SE 0.03). Species from 2 genera were observed at REA sites: *Stichopus* and *Actinopyga. Stichopus* was the only genus recorded in the west region at ANA-03, the site with the highest sea cucumber density of 5 organisms 100 m^{-2}, and *Actinopyga* was observed only at ANA-06 in the western part of the south region. Among all towed-diver surveys around this island, the survey completed in the northern part of the west region had the highest mean density of sea cucumbers with 0.85 organisms 100 m^{-2};

segment densities from this survey ranged from 0 to 2.88 organisms 100 m^{-2} (Fig. 9.7.1c). The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.14 organisms 100 m^{-2}, recorded in the western part of the south region; segment densities ranged from 0 to 0.86 organisms 100 m^{-2}.

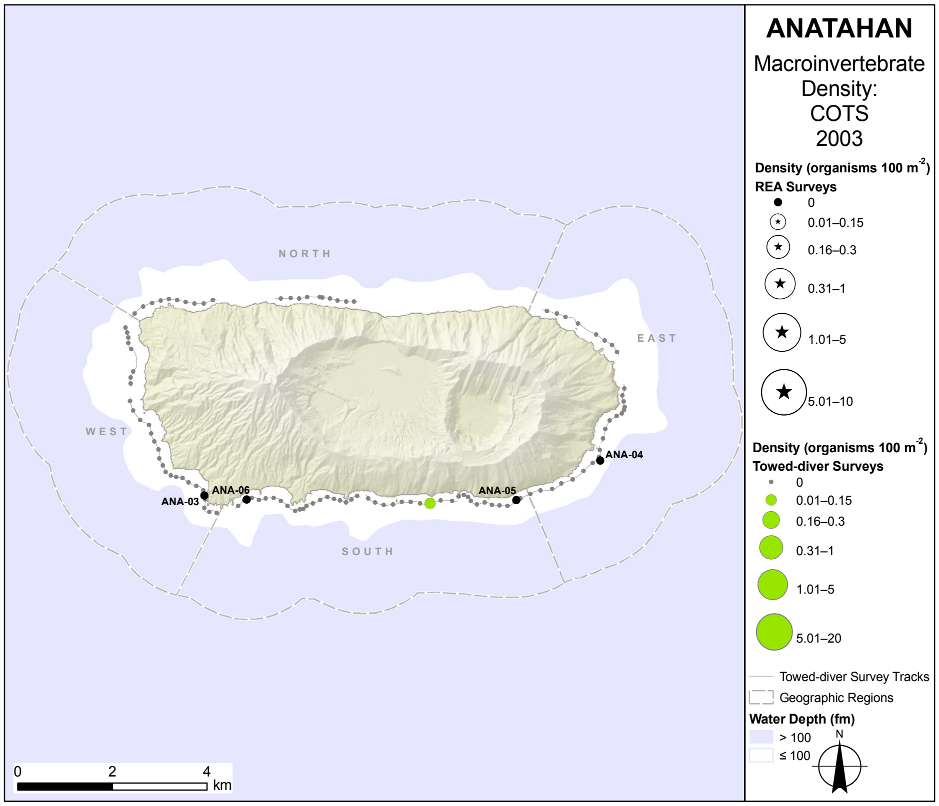


Figure 9.7.1b. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003.

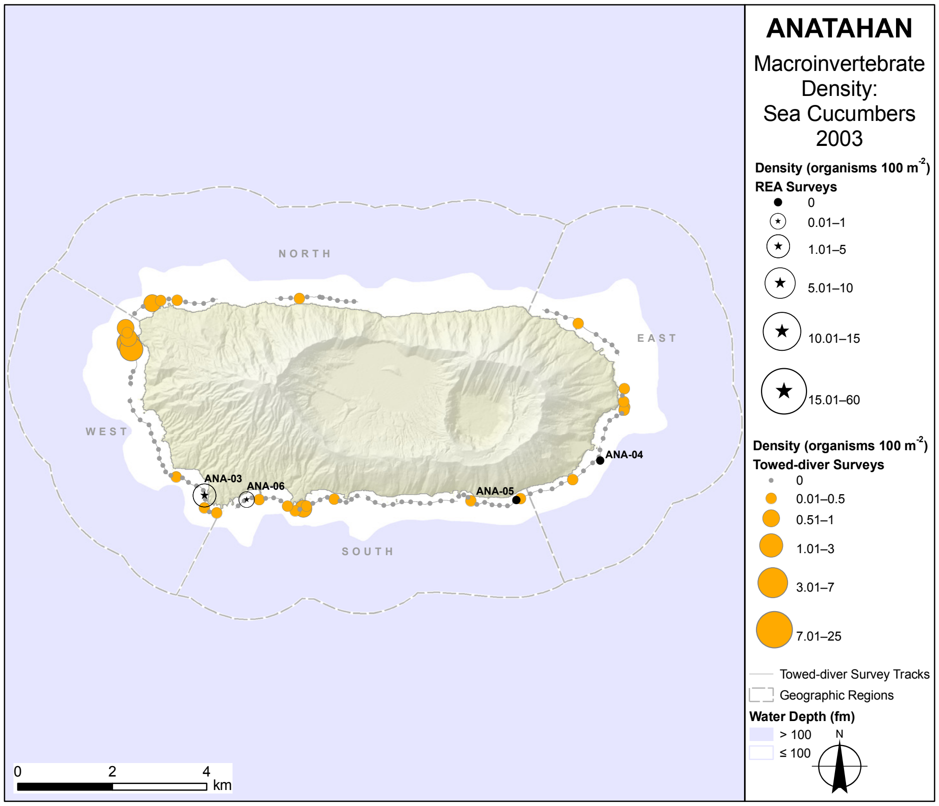


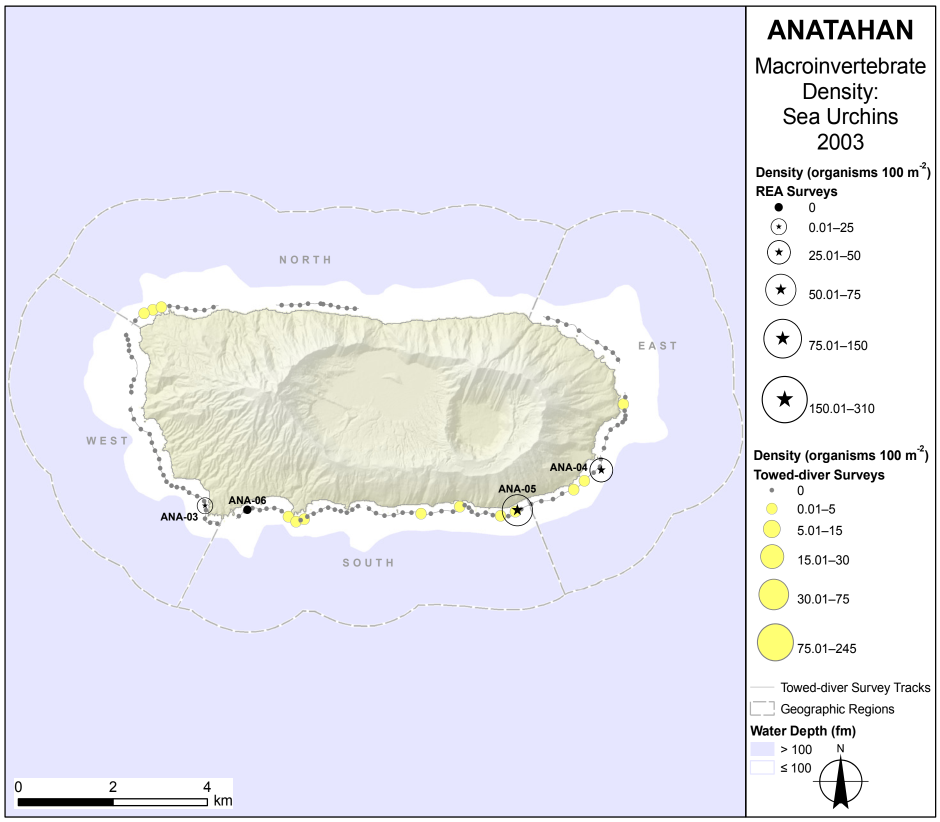
Figure 9.7.1c. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003.

Sea Urchins

During MARAMP 2003, sea urchins were observed at 3 of the 4 REA sites surveyed and in 6 of the 12 towed-diver surveys conducted around Anahatan. The overall sample mean of sea urchin density from REA surveys was 26.5 organisms 100 m^{-2} (SE 16.99), and the islandwide mean density from towed-diver surveys was 0.07 organisms 100 m^{-2} (SE 0.04). Survey results suggest that sea urchins were most abundant at ANA-05 in the eastern part of the south region with 72 organisms 100 m^{-2} (Fig. 9.7.1d). Rock-boring urchin species from the genus *Echinostrephus* accounted for 97% of sea urchins recorded at ANA-05 in the south region. Overall, species from the genus *Echinostrephus* accounted for 97% of sea urchins observed at all REA sites surveyed at Anatahan*.* Other genera found at Anatahan included *Echinothrix* and *Diadema*.

Among all towed-diver surveys conducted around Anatahan in 2003, the survey completed in the eastern part of the south region had the highest mean density of sea urchins with 0.69 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 4.68 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 0.04 organisms 100 m^{-2}, recorded in the western part of the south region; segment densities ranged from 0 to 0.21 organisms 100 m^{-2}.

Figure 9.7.1d. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003.



9.8 Reef Fishes

9.8.1 Reef Fish Surveys

Anatahan Volcano erupted on May 10, 2003, and by the time that MARAMP 2003 occurred in September 2003, underwater visibility was low and towed-diver fish surveys were restricted to areas where visibility was > 5 m. Because low-level volcanic activity continued through 2008, fish surveys were not completed at Anatahan in 2005 or 2007.

Large-fish Biomass

During MARAMP 2003, 12 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around Anatahan. The overall estimated mean biomass of large fishes around this island, calculated as weight per unit area, was 0.22 kg 100 m^{-2} (SE 0.07). Biomass values for large fishes were highest along the southeastern coast, where jacks (Carangidae) and snappers (Lutjanidae) were observed (Fig. 9.8.1a). Jacks accounted for the greatest proportion (38%) or 0.08 kg 100 m^{-2} of overall mean large-fish biomass. The bluefin trevally (*Caranx melampygus*) was the major jack species, contributing 30% of overall mean biomass of large fishes. Reef sharks (Carcharhinidae) and snappers were the next-most important families in terms of biomass, accounting for 0.05 kg 100 m^{-2} and 0.04 kg 100 m^{-2} of overall mean large-fish biomass. During this survey period, 7 reef sharks were observed: 5 grey reef sharks (*Carcharhinus amblyrhynchos*) and 2 whitetip reef sharks (*Triaenodon obesus*). Grey reef sharks contributed 81% of shark biomass at Anatahan. The twinspot snapper (*Lutjanus bohar*) was the dominant snapper species by biomass, accounting for 84% of snapper biomass.

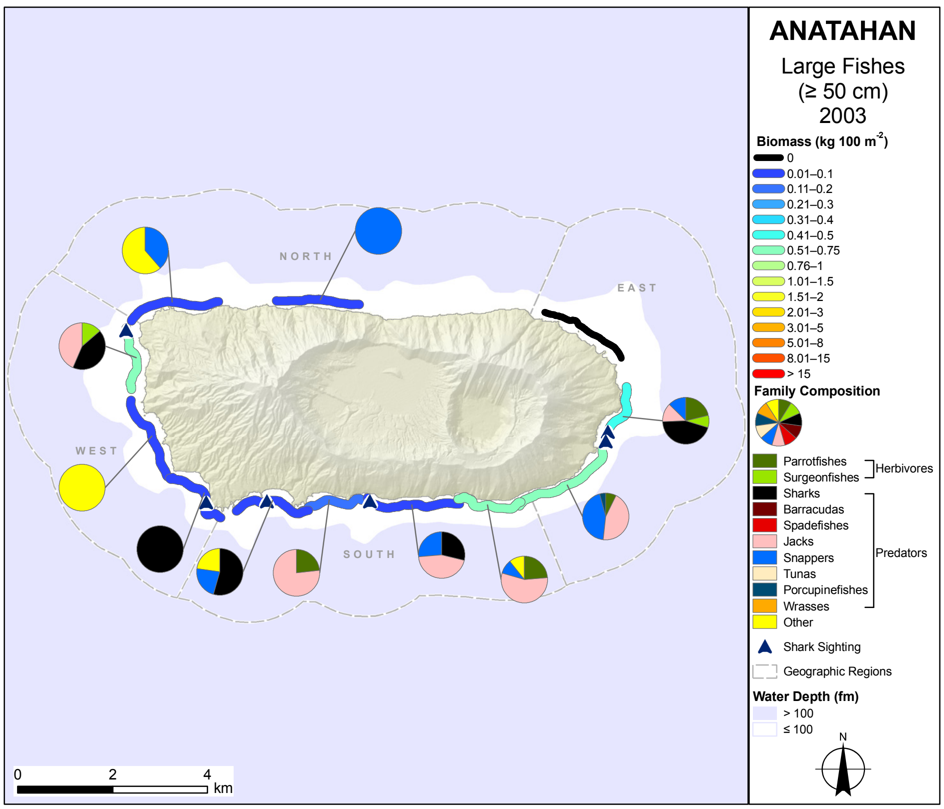


Figure 9.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and individual shark sightings from towed-diver fish surveys of forereef habitats conducted around Anatahan during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside the survey area over which it is shown.

Total Fish Biomass and Species Richness

Total fish biomass for the 3 REA sites surveyed in forereef habitats at Anatahan during MARAMP 2003 was low compared to other sites in the Mariana Archipelago, with an overall sample mean of 2.81 kg 100 m^{-2} (SE 2.55). The highest biomass of 7.90 kg 100 m^{-2} was observed at REA site ANA-03 in the west region (Fig. 9.8.1b). Overall, snappers accounted for the largest proportion (34%) or 0.94 kg 100 m^{-2} of total fish biomass, and the twinspot snapper (*Lutjanus bohar*) contributed 51% of snapper biomass and 17% of total fish biomass. Surgeonfishes (Acanthuridae) were the second-most important family in terms of biomass, accounting for 0.47 kg 100 m^{-2} of total fish biomass. The striated surgeonfish (*Ctenochaetus striatus*) contributed 67% of surgeonfish biomass. No sharks were observed during this survey period.

Based on REA surveys conducted during MARAMP 2003, species richness was relatively low at Anatahan with a range of 1–34 species 100 m^{-2}. The highest diversity was found at ANA-03. Wrasses (Labridae) and damselfishes (Pomacentridae) were observed with the greatest diversity, each with 9 species recorded. The cleaner wrasse (*Labroides dimidiatus*) was the most numerically abundant wrasse species. Jacks (Carangidae) dominated counts, and the island trevally (*Carangoides orthogrammus*) was the most abundant jack species with > 20 individuals 100 m^{-2} recorded, nearly all of them < 10 cm in size. The brown surgeonfish (*Acanthurus nigrofuscus*) was the second-most numerically abundant species with 6.2 individuals 100 m^{-2} recorded.

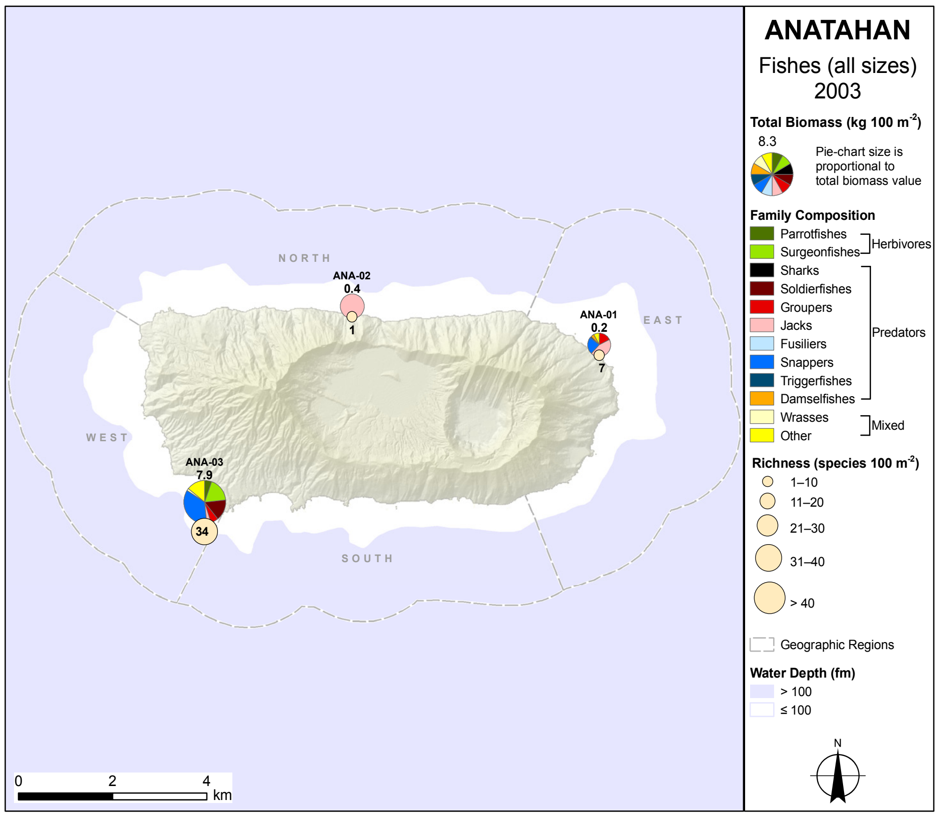


Figure 9.8.1b. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Anatahan during MARAMP 2003.

9.9 Marine Debris

9.9.1 Marine Debris Surveys

During MARAMP 2003, only 1 sighting of a man-made object in the south region was recorded during the 12 towed-diver surveys conducted around the island of Anatahan (Fig. 9.9.1a). No additional descriptive information about this observation was documented. No munitions, wrecks, or other man-made objects were observed. Observations of debris are positive identifications, but absence of reports does not imply lack of debris.

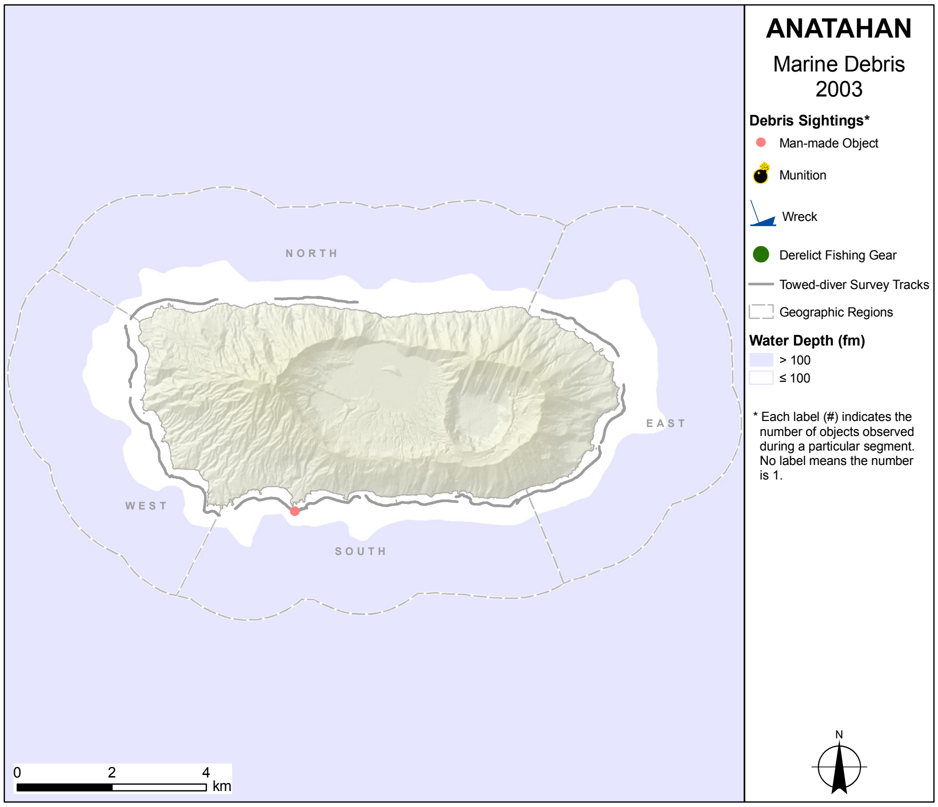


Figure 9.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Anatahan during MARAMP 2003. The single, pink symbol indicates the presence of a man-made object.

9.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the island of Anatahan are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components. In addition to this island-level analysis, evaluations on an archipelagic scale of various ecosystem elements and their potential relationships across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Anatahan as well as the other 13 islands covered in this report.

In May 2003, Anatahan experienced a large volcanic eruption from its eastern crater, the first eruptive activity recorded on this island. This eruption was accompanied by flows of volcanic ash, dust, and rocks as well as explosions of steam, mud, and other volcanic material. Much of the vegetation on Anatahan was damaged by this volcanic activity (Fig. 9.10a). Extensive ash plumes from this eruption were carried west by prevailing winds. The effects of this volcanic activity overwhelmed any discernable patterns in the distribution and condition of the coral reef ecosystem components that may have been present around Anatahan before 2003.

MARAMP surveys at Anatahan, conducted only 4 months after this major eruption in September 2003, were hampered by the reduced visibility caused by extensive ash deposits. Because of these poor conditions and safety concerns, no biological surveys were attempted at this island in 2005 or 2007, although oceanographic instruments were deployed and recovered.

Figure 9.10a. Anatahan, devoid of vegetation after the May 2003 volcanic eruption, as seen from the NOAA Ship *Hi`ialakai* in 2005. *NOAA photo by Robert Schroeder*

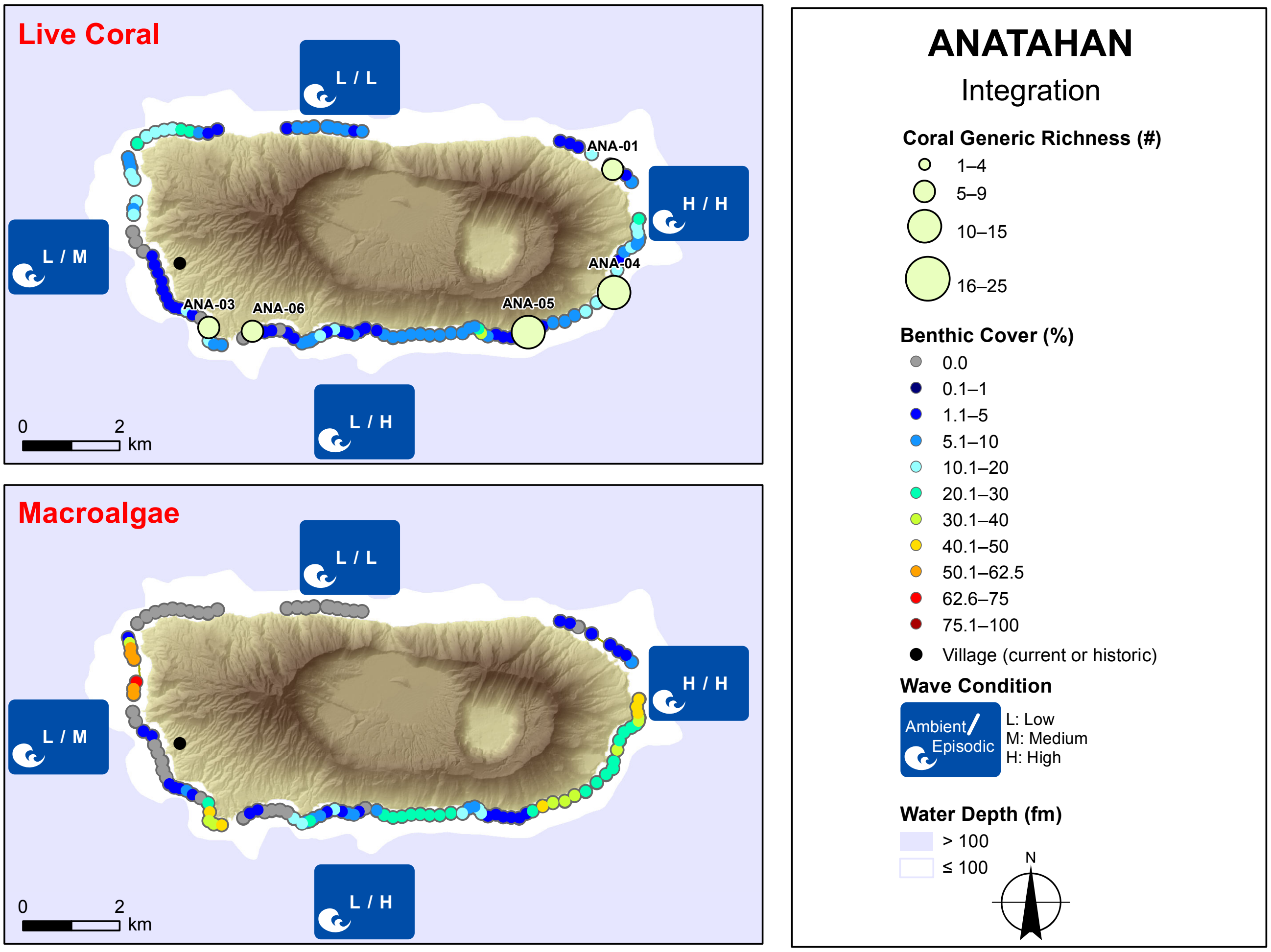


Figure 9.10b. Cover (%) observations of live hard corals and macroalgae from towed-diver surveys and coral generic richness from REA surveys conducted on forereef habitats around Anatahan during MARAMP 2003. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region. The black dot on the west side of Anatahan shows the approximate location of uninhabited Anatahan village.

The north and west regions appeared most affected by the volcanic eruption in 2003. In both regions, divers observed a seabed covered with a thick layer of ash above which only high coral pinnacles protruded. Live-hard-coral cover from towed-diver surveys in the north and west regions ranged from 0% to 30% (Fig. 9.10b). Cover estimates for both macroalgae and crustose coralline red algae were similarly low in both regions, compared to levels observed for other regions at Anatahan, with the exception of a section of the survey conducted in the west region, with macroalgal cover of 30%–75% (Fig. 9.10b). TOAD surveys conducted north of Anatahan, at greater depths (up to 100 m) than depths for towed-diver surveys, suggested a substrate of volcanic ash with no live corals or macroalgae, at least as observed in the analyzed video frames. Because of low visibility, no REA benthic surveys for corals or algae were conducted in these areas of high ash cover. The dominant habitats, described during towed-diver surveys, were sand-flats and reefs north of Anatahan and carbonate pavement, sand-flats, and boulders to the west. The abundance of recently dead corals and diversity of dead coral skeletons, observed during towed-diver surveys, suggested that reefs north of Anatahan may have been extensive prior to the eruption in 2003.

Both east and south of Anatahan, the habitat was described as sand-flats with boulders during towed-diver surveys. The observed ashfall was much thinner in the east and south regions than in the other regions, with a veneer of fine ash covering the reef rather than a thick blanket of ash. Prevailing wind at the time of the eruption in 2003 likely carried the ash plume to the west. As in the west and north regions, live coral cover was low, with means of 0%–30% from the 7 towed-diver surveys conducted in the east and south regions. The only exception was the coral cover of 30.1%–40% observed for 1 segment of a survey conducted in the south region (Fig. 9.10b). Macroalgal cover, with means of 0%–50%, was higher in the south and east regions than in the north region (Fig. 9.10b). Southeast of Anatahan, reefs appeared slightly less affected by volcanic ash than reefs observed elsewhere at this island. The highest levels of coral density and generic richness at Anatahan were found at REA sites ANA-04 and ANA-05 in the east and south regions (Fig. 9.10b), although live coral cover from nearby towed-diver surveys was low with means < 30%. Macroalgal cover from towed-diver surveys in the southern part of the east region was moderately high, within a range of 20.1%–50%, compared with results from other surveys conducted at Anatahan, and the highest algal diversity was recorded at ANA-04.

Biomass of large fishes (≥ 50 cm in TL) around Anatahan likely was underestimated during towed-diver surveys, as a result of the poor visibility caused by the suspended ash in the water column. Notably, estimated total fish biomass was low from REA surveys of fishes of all sizes and species conducted in the north region, where visibility was especially low. Visibility, at ~ 12 m, was greater in the southern part of the west region at ANA-03, where the highest values of total fish biomass (7.9 kg 100 m^{-2}) and species richness (34 species 100 m^{-2}) at Anatahan were observed.

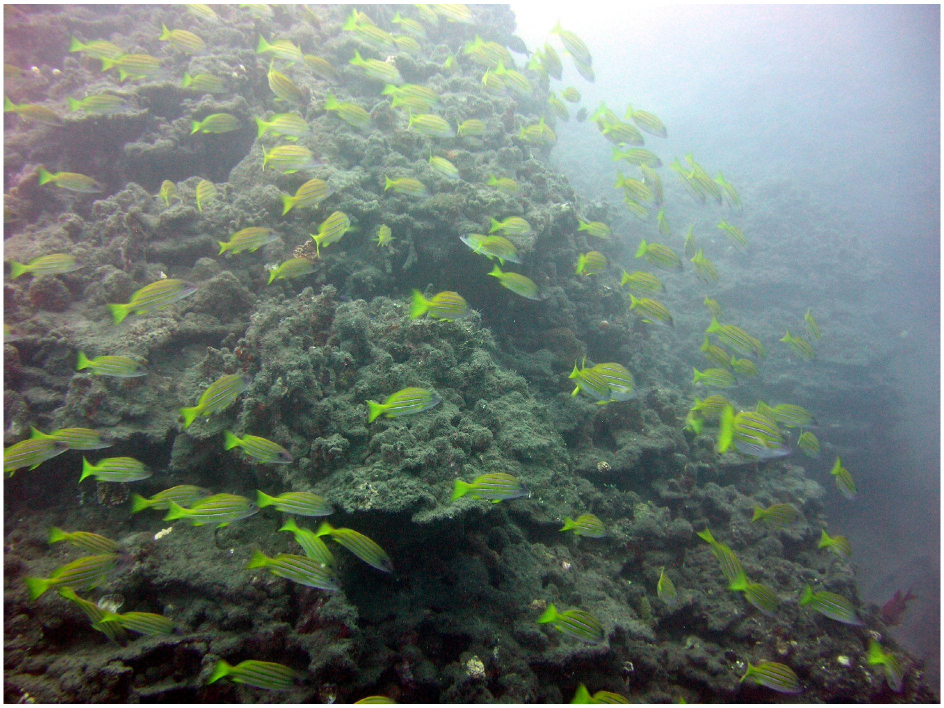


Figure 9.10c. Snappers (Lutjanidae) above ash-silted corals at Anatahan. *NOAA photo by Robert Schroeder*

Although the volcanic activity of Anatahan has not reached the level of a major eruption since 2003, ash likely continues to impact the coral reef ecosystems around this island. During MARAMP 2003, divers noted that rainfall washed ash from this island onto adjacent reefs. CTD casts conducted in 2007 in the south region at a depth of 10 m recorded low beam transmission (~ 91 %), and examination of vertical CTD profiles showed highly turbid waters at depths of 5–10 m, a result of ash and other volcanic debris in the water column (Figs. 9.4.1f and g in Section 9.4.1: "Hydrographic Data"). During surveys conducted at Anatahan in May 2009, divers reported that ash continued to cover much of the substrate around this island (Fig. 9.10c).

9.11 Summary

MARAMP integrated ecosystem observations provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats around Anatahan. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods and Operational Background," and specific limitations of the data or analyses presented in this Anatahan chapter also are included in the relevant discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of the fish and benthic communities and the overall ecosystem around Anatahan, relative to the ecosystems around all the other islands in the Mariana Archipelago, are discussed in Chapter 3: "Archipelagic Comparisons."

This section presents an overview of the status of coral reef ecosystems around the island of Anatahan as well as some of the key natural processes influencing these ecosystems:

- The southernmost island of the CNMI's Northern Islands Municipality, Anatahan has a land area of 33.91 km^2 and is located 120 km north of Saipan and 40 km south of Sarigan.

- Because of increased seismic and thermal activity of Anatahan Volcano, this island has been mostly uninhabited in recent decades. Anatahan village, located on the southwestern part of this island, was covered with ash from the major volcanic eruption in 2003.

- The full extent to which the marine habitats have been affected by recent volcanic activity is not known. During the limited MARAMP surveys conducted in 2003, ~ 4 months after eruptions began in May 2003, divers observed large volumes of ash covering many of the coral reefs around Anatahan, mainly on the northern and western sides. Ash plumes continued intermittently through 2008 and likely have affected other areas at this island as a result of variable wind conditions.

- Wave model output shows ambient trade wind swells impact the east region. Episodic wave energy from storm tracks impact the south and east regions and to a lesser extent the west region.

- In 2005, and to a lesser extent 2007, the waters surrounding Anatahan were a deep brown color because of the copious amounts of ash and volcanic input. Visibility was < 0.6 m, and no benthic or fish surveys were conducted in either year. This entire island was void of vegetation, so any precipitation likely resulted in strong terrigenous input to surrounding waters.

- The overall mean for live coral cover around Anatahan was 8%, estimated from towed-diver surveys conducted during MARAMP 2003.

- Generic diversity for marcroalgae at Antahan, based on REA surveys conducted in 2003, was much higher in the east region than in the west region. The highest macroalgal cover from a towed-diver survey conducted at Anatahan was recorded in the west region. The north region was largely devoid of macroalgae. Crustose-coralline-red-algal cover was very low in the north and west regions, compared to results from other islands in the Mariana Archipelago.

- Because of reduced visibility due to ash in the water column from recent volcanic activity, fish surveys in 2003 were restricted to areas where visibility was estimated at > 5 m. As a result, surveys were conducted haphazardly around this island, and the overall mean biomass of large fishes (≥ 50 cm in TL) was very low compared to the levels observed at other islands in this archipelago. Biomass of large fishes from towed-diver surveys was highest along the southeastern coast, where jacks (Carangidae) and snappers (Lutjanidae) were observed. This area appeared to be least affected by ashfall.

- Total fish biomass from REA surveys of fishes of all sizes and species conducted off north Anatahan during MARAMP 2003 was very low compared to values found at other islands in the Mariana Archipelago, with surveys hampered by reduced visibility. The highest total fish biomass was seen in the west region at ANA-03, where snappers accounted for the largest proportion of total fish biomass at that site. No sharks were recorded during REA surveys in 2003.

- Very few giant clams, crown-of-thorns seastars (*Acanthaster planci*), or sea cucumbers were observed in 2003 during both towed-diver and REA surveys conducted around Anatahan.

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